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MILITARY HYDROLOGY

Report 17

A QUASI-CONCEPTIONAL LINEAR MODEL FOR SYNTHESIS OF DIRECT RUNOFF WITH POTENTIAL APPLICATION TO UNGAGED BASINS

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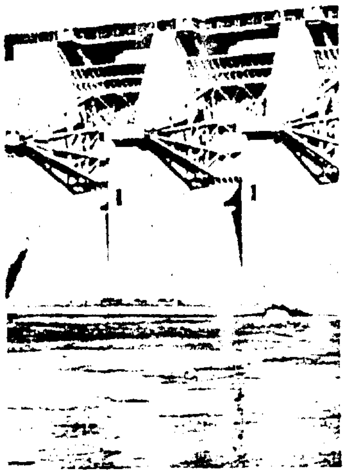

by

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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

July 1989

Report 17 of a Series

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Contract No. DACA39-81-C-0005
DA Project No. 4A762719AT40
Task Area 80, Work Unit 041

Monitored by Environmental Laboratory
US Army Engineer Waterways Experiment Station
PO Box 631, Vicksburg, Mississippi 39181-0631

ENVIRONMENTAL LABORATORY

89 9 05 103

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) Miscellaneous Paper EL-79-6
6a. NAME OF PERFORMING ORGANIZATION Mississippi State University Department of Civil Engineering 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION USAEWES Environmental Laboratory
6c. ADDRESS (City, State, and ZIP Code) Mississippi State, MS 39762-5610	7b. ADDRESS (City, State, and ZIP Code) PO Box 631, Vicksburg, MS 39181-0631
8a. NAME OF FUNDING/SPONSORING ORGANIZATION US Army Corps of Engineers 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract No. DACA39-81-C-0005
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. | PROJECT NO. See reverse. | TASK NO. 80 | WORK UNIT ACCESSION NO. 041

11. TITLE (Include Security Classification)
Military Hydrology; Report 17, A Quasi-Conceptual Linear Model for Synthesis of Direct Runoff with Potential Application to Ungaged Basins

12. PERSONAL AUTHOR(S)
Singh, Vijay P.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Report 17 of a series	FROM ____ TO ____	July 1989	99

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Geomorphology, Streamflow, Hydrology, Streamflow forecasting, Military hydrology

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A quasi-conceptual linear model is developed for synthesis of the instantaneous unit hydrograph (IUH) by employing drainage network properties. This IUH is then employed in convolution for synthesis of the direct runoff resulting from a rainfall event. Because the approach contains parameters that can be determined from basin morphology, it is potentially applicable to ungaged basins. A computer model, designated as GMHS, is developed using this approach for hydrograph synthesis. The model is verified on five small agricultural basins. The model results compare well with observations in light of accuracy of the parameters and data.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code) | 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

PREFACE

The work reported herein was conducted for the US Army Engineer Waterways Experiment Station (WES) under the Department of the Army Project No. 4A762719AT40, "Mobility and Weapons Effects Technology," Task Area 80, "Combat Engineering," Work Unit 041, "Tactical Streamflow Forecast Procedures for Mobility/Countermobility Operations," sponsored by Headquarters, US Army Corps of Engineers (HQUSACE). Dr. Clemens A. Meyer was the HQUSACE Technical Monitor.

The study was conducted and the report written by Dr. Vijay P. Singh of the Department of Civil Engineering, Mississippi State University, Mississippi State, MS, under WES Contract No. DACA39-81-C-0005.

Dr. U. S. Panu, formerly a member of the civil engineering faculty at Mississippi State University, assisted in the initial stages of this study. His work was supported by funds provided by WES, the National Science Foundation, and the US Department of Interior through the Louisiana Water Resources Research Institute.

The contract was monitored technically by Mr. John G. Collins, Environmental Constraints Group (ECG), Environmental Laboratory (EL), WES, under the direct supervision of Mr. Malcolm P. Keown, Chief, ECG, and under the general supervision of Dr. Victor E. LaGarde III, Chief, Environmental Systems Division, EL, and Dr. John Harrison, Chief, EL. This report was edited by Ms. Lee T. Byrne of the Information Technology Laboratory.

COL Dwayne G. Lee, EN, is the Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

This report should be cited as follows:

Singh, V. P. 1989. "Military Hydrology; Report 17, A Quasi-Conceptual Linear Model for Synthesis of Direct Runoff with Potential Application to Ungaged Basins," Miscellaneous Paper EL-79-6, prepared by Mississippi State University, Starkville, MS, for the US Army Engineer Waterways Experiment Station, Vicksburg, MS.

CONTENTS

MILITARY HYDROLOGY

A QUASI-CONCEPTUAL LINEAR MODEL FOR SYNTHESIS OF DIRECT RUNOFF WITH POTENTIAL APPLICATION TO UNGAGED BASINS

PART I: INTRODUCTION

Background

1. Under the Meteorological/Environmental Plan for Action, Phase II, Headquarters, US Army Corps of Engineers (HQUSACE), has been tasked to implement a research, development, testing, and evaluation program that will provide the US Army with (a) environmental effects information needed to operate in a realistic battlefield environment and (b) the capability for near-real time environmental effects assessment of military materiel and operations in combat. In response, the Directorate for Research and Development, HQUSACE, initiated the AirLand Battlefield Environment (ALBE) Thrust Program. Under this new initiative, technologies to provide the field Army with the operational capability to perform and exploit battlefield effects assessments for tactical advantage will be developed.

2. Military hydrology, one facet of the ALBE Thrust, is a specialized field of study that deals with the effects of surface and subsurface water on the planning and conduct of military operations. In 1977, HQUSACE approved a military hydrology research program; management responsibility was subsequently assigned to the Environmental Laboratory, US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS.

3. The objective of military hydrology research is to develop an improved hydrologic capability for the Armed Forces with emphasis on applications in the tactical environment. To meet this overall objective, research is being conducted in four thrust areas: (a) weather-hydrology interactions, (b) state of the ground, (c) streamflow, and (d) water supply.

4. Previously published military hydrology reports are listed on the inside of the back cover. This report contributes to the ability to calculate streamflow, which is the basis for developing improved flood-forecasting capabilities for use on ungaged watersheds.

5. Streamflow synthesis from ungaged basins has long been a subject of scientific inquiry. A survey of hydrologic literature (Dooge 1976, Singh 1978) suggests three fundamental approaches: (a) empirical, (b) conceptual, and (c) physically based. The first approach comprises empirical relations for determining some key characteristics of streamflow hydrographs, such as lag time, peak discharge, time to peak, or hydrograph duration. These relations are developed by standard curve-fitting methods based on data from gaged basins and are then applied to ungaged basins with the hope that they will yield satisfactory results. Although such relations can be useful in particular cases, this approach is, in general, not scientifically sound and is often discarded in favor of one of the other approaches.

6. The second approach basically incorporates what are referred to as systems analysis and synthesis techniques (Dooge 1973, Nash and Foley 1982). These techniques use spatially lumped parameters, although attempts have been made to make them quasi-distributed (Singh 1979). In other words, they do not explicitly take into account spatial variability of rainfall or runoff, even though attempts have been made to partly relax this restriction (Singh 1978). The major thrust has been to develop the effective rainfall-direct runoff relationship. Effective rainfall denotes that portion of rainfall which becomes direct runoff, whereas the remaining portion is denoted as abstraction. Direct runoff is that portion of streamflow which is composed of surface runoff and quick interflow. It is implicit here that the volume of direct runoff is equal to the volume of effective rainfall. A classic example is the unit hydrograph approach, which is the hydrograph of direct runoff at the outlet of a basin resulting from an effective rainfall of unit volume and of given duration occurring uniformly in time and space. It is always associated with the duration of effective rainfall; that is, as this duration changes, so does the unit hydrograph. Most of these techniques therefore revolve around estimating the effective rainfall, separating the streamflow hydrograph, and employing a spatially lumped form (integrated over space) of the continuity equation in conjunction with a storage-discharge relation. The effective rainfall determination and hydrograph separation are somewhat arbitrary, since these are not well-defined concepts and are based more on convenience than on physical realism.

7. On the other hand, geomorphic techniques have recently been advanced for hydrograph synthesis (Boyd 1978; Boyd, Pilgrim, and Cordery 1979;

Rodriguez-Iturbe and Valdes 1979; Rodriguez-Iturbe, Devoto, and Valdes 1979; Valdes, Fiallo, and Rodriguez-Iturbe 1979; Gupta, Waymire, and Wang 1980; Wang, Gupta, and Waymire 1981; Rodriguez-Iturbe 1982). These techniques have added a new dimension to application of geomorphology to the effective rainfall-direct runoff relationship. However, they remain to be tested on a wide variety of gaged basins and have yet to be applied to ungaged basins.

8. The second approach is promising but has shortcomings that need to be properly addressed. First, only that portion of the hydrograph attributable to direct runoff is synthesized. Second, the concepts of effective rainfall and direct runoff are not well defined. Third, the amount of rainfall infiltrating into the ground is determined somewhat arbitrarily, although there is increasing evidence to support the view that infiltration is one of the most important factors affecting the streamflow hydrograph. Fourth, spatial variability in basin characteristics affecting infiltration, detention and depression storage, and runoff is not accounted for. Fifth, spatial variability of rainfall cannot be handled analytically in a convenient manner. Sixth, the parameters appearing in these approaches often have little physical significance, or they have yet to be correlated dependably with physical measurements.

9. The third approach employs, in some form, principles of mathematical physics which are the laws of conservation of mass, momentum, and energy (Woolhiser 1982). The development of techniques associated with this approach has paralleled, for the most part, those of the second approach; that is, development of the effective rainfall-direct runoff relationship has been the major thrust. The consequence has been twofold: (a) the techniques have been refined little more than those of the second approach and (b) they have been less than practical working tools. Their extension to ungaged basins is neither convenient nor intuitively acceptable.

10. It should be pointed out that a few isolated attempts have been made to abandon the concept of effective rainfall and to consider infiltration and runoff simultaneously during and after the occurrence of a rainfall episode (Smith and Woolhiser 1971; Rovey and Woolhiser 1977; Singh 1976a, 1976b; Singh and Agiralioglu 1980, 1981a, 1981b, 1981c; Sherman and Singh 1976a, 1976b, 1978, 1982). However, these studies have been concerned principally with overland flow and not with other components of streamflow.

11. Although physically based techniques have been successfully applied to analyses of streamflow hydrographs, their application to hydrograph synthesis for ungaged basins has yet to be made. The reasons are manyfold. First, these approaches have not been systematically validated. Second, parameters such as friction factor have been determined by data-fitting and not from physical measurements. It is, therefore, not clear if these parameters can indeed be determined from commonly available measurements and have the same meaning in the context of streamflow synthesis as they are intended to have. Third, a systematic data base has not been developed for obtaining an objective validation of these techniques and their subsequent application to ungaged basins. Fourth, dynamic interactions with subsurface flow components of streamflow have been evaded. Fifth, space-time quantification of friction, geometric complexity, variability of rainfall, and variability in basin characteristics affecting infiltration and runoff characteristics have been some of the persistent problems yet to be resolved objectively. It is not clear how much detailed accounting of these factors is needed in streamflow synthesis. No single study can address all of these and related issues.

12. Close scrutiny may suggest that a major breakthrough in streamflow synthesis on ungaged basins is most likely with a conceptual approach. Recent studies on application of geomorphology to basin hydrology, cited previously, have blended geomorphologic laws with modern hydrological systems analysis and synthesis techniques. As a result, they may be on the verge of providing a unified framework for hydrograph synthesis for ungaged basins. This motivated the use of a quasi-conceptual approach in this study.

Objectives

13. The objectives of this study are (a) to develop a quasi-conceptual linear model for direct runoff hydrograph synthesis potentially applicable to ungaged basins, (b) to test this model on gaged basins, and (c) to develop a computer code for ready use by field engineers.

Scope

14. The theoretical development of the model is presented in Part II of this report. Part III includes an explanation of the model structure and a

brief description of each subroutine. In Part IV applications of the model on five experimental agricultural watersheds are discussed. An illustrative example showing the calculations required is presented in Appendix A. User instructions are included in Appendix B and a listing of the program code in Appendix C.

PART II: QUASI-CONCEPTUAL FRAMEWORK

15. For implicity, the assumption is made that the transformation of effective rainfall to direct runoff is linear and time-invariant. The problem of direct runoff hydrograph synthesis then reduces to determining the instantaneous unit hydrograph (IUH) utilizing basin morphometry. The approach presented here was developed by Rodriguez-Iturbe and Valdes (1979) and generalized by Gupta, Waymire, and Wang (1980).

16. Let it be supposed that an instantaneous burst of effective rainfall having unit volume is injected into the basin. This burst is composed of a large number of particles n, which are noninteracting. Each of these particles will stay in the basin for a finite period of time T_i, $i = 1, 2, 3, \ldots, n$. T_i can be referred to as holding time or travel time. If it is assumed that T_i, $1 \leq i \leq n$, are random variables, then these must be independently distributed by virtue of the assumption of noninteraction of particles. It may be added that the assumption of T_i, $i = 1, 2, \ldots, n$, being random is physically plausible.

17. T_i, $i = 1, 2, \ldots, n$, depends on where the i^{th} particle lands on the basin and as a consequence the path it takes to reach the mouth. The path is uniquely determined by where it lands in the basin. Obviously, T_i also depends on many other factors encountered along the path. The paths available for these particles to follow are determined by the basin geomorphology in general and the channel network in particular.

18. Let the basin be of W-order. Then the streams S_i, of order i, $i = 1, 2, \ldots, W$, are available in the basin; clearly, S_i denotes the i^{th} order streams. In this approach, channel networks are ordered according to the Strahler ordering scheme (Smart 1972). A particle goes through a number of states determined by the structure of the drainage network as it travels from its point of landing to the outlet of the basin. These states are composed of overland regions and channels of different orders.

19. A channel state of order i is defined by C_i, $i = 1, 2, \ldots, W$, as the collection (ensemble) of all the Strahler channels of that Strahler order. Likewise, an overland region state of order i is defined by r_i, $i = 1, 2, \ldots, W$, as the collection of all the regions draining directly into the i^{th} ordered channels. Then each particle will initially be found in one of the overland states r_i, $i = 1, 2, 3, \ldots, W$, and its movement will be

governed by the following rules as a consequence of the Strahler ordering scheme: (a) the only possible transitions out of the state r_i are of the form $r_i \rightarrow C_i$, $1 \leq i \leq W$; (b) the only possible transitions out of the state C_i are of the form $C_i \rightarrow C_j$, $j > i$, $2 \leq j \leq W + 1$, $1 \leq i \leq W$; and (c) there is a state C_{W+1} , defined as a trapping state. Transitions out of the trapping state are impossible.

20. These rules define a collection S of paths, $S = \{s\}$ or $s \varepsilon S$ which a particle may follow through to the trapping state, that is, the outlet of the basin. For a basin of order W , there are 2^{W-1} possible paths. To illustrate, consider a third-order basin as shown in Figure 1, $W = 3$. The path space $S = \{s_1, s_2, s_3, s_4\}$ consists of the following paths:

path s_1: $r_1 \rightarrow C_1 \rightarrow C_2 \rightarrow C_3 \rightarrow C_4$
path s_2: $r_1 \rightarrow C_1 \rightarrow C_3 \rightarrow C_4$
path s_3: $r_2 \rightarrow C_2 \rightarrow C_3 \rightarrow C_4$
path s_4: $r_3 \rightarrow C_3 \rightarrow C_4$

21. These specify the spatial paths of a particle through a geomorphic network of channels and overland regions. The travel time of a particle must therefore be specified by the particular path it takes to reach the outlet. The travel time T_S is the sum of the times spent by the particle in the various states forming its path.

$$T_S = T_{x1} + T_{x2} + \ldots + T_{xM}, \; M > 1 \qquad (1)$$

where T_x is the time a particle spends in the state x ($x = r_i$ or C_i for some i) and M is the number of states. T_x is assumed to be a random variable. T_x can have an arbitrary probability density function (PDF), and for different states x and y , T_x and T_y can have different PDF's. However, T_x and T_y are assumed to be independent for $x \neq y$. The validity of this assumption seems plausible from a physical standpoint.

22. If T_B denotes the random time that a particle spends in the basin, then

$$T_B = \sum_{s \varepsilon S} I_s T_s \qquad (2)$$

where I_s is the indicator function for the path s ; that is, $I_s = 1$ if the particle follows the path s , and $I_s = 0$ otherwise. The PDF of T_B , denoted by $f_B(t)$, is obtained as follows:

23. Let A_{ri} be the ratio of the area of r_i to the basin area A_w , and $P_{ci,cj}$ the proportion of channels of order i merging into channels of order j, $j > i$, $2 < j \leq W + 1$. Obviously $P_{cW,cW+1} = 1$; this is not strictly true since a basin of any given order may outlet into a stream several orders higher. However, this is convenient and does not affect the model. Similarly, $P_{ri,ci} = 1$. Then for a path $s \varepsilon S$ of the form $s = \{x_1, x_2, \ldots, x_k\}$ where $x_1, x_2, \ldots x_k \varepsilon \{C_1, C_2, \ldots, C_W; r_1, r_2, \ldots, r_W\}$. The path probability function is defined as

$$p(s) = A_{x1} \cdot P_{x1,x2} \ldots P_{xk-1,xk} \tag{3}$$

It should be emphasized that the paths are all distinct. Therefore, the probability of $T_B < t$ is

$$\begin{aligned} P(T_B < t) &= \sum_{s \varepsilon S} P(T_s < t) \cdot p(s) \\ &= \sum_{s \varepsilon S} F_{x1} * F_{x2} * \ldots * F_{xk}(t) \cdot p(s), \end{aligned} \tag{4}$$

$$s = \{x_1, x_2, \ldots, x_k\}$$

where

t = specific time

F_x = cumulative density function of T_x

$*$ = convolution operation

Differentiation with respect to t on both sides yields

$$f_B(t) = \sum_{s \varepsilon S} f_{x1} * f_{x2} * \ldots * f_{xk} \cdot p(s) \tag{5}$$

where f_x denotes the PDF of T_x . Gupta, Waymire, and Wang (1980) have established the equivalence of $f_B(t)$ and the IUH, $h(t)$. Therefore,

$$h(t) = \sum_{s \varepsilon S} f_{x1} * f_{x2} *\ldots* f_{xk} \cdot p(s) \tag{6}$$

where $h(t)$ is the result of an instantaneous burst of effective rainfall of unit volume. If the effective rainfall takes places continuously for some time, then the direct runoff can be determined by invoking the basin linearity. Stated simply, the convolution integral can be employed as

$$Q(t) = \int_0^t h(t - \tau)\ I(\tau)\ d\tau \tag{7}$$

where

$Q(t)$ = discharge at t

$I(t)$ = effective rainfall

τ = variable of integration

Thus, the direct runoff hydrograph synthesis reduces to synthesis of $h(t)$ using Equation 6.

24. In Equation 6 the path probability function $p(s)$ can be specified completely from the drainage network morphometry. However, specification of f_{xi} cannot be entirely based on physical considerations. For simplicity, f_{xi} is assumed to be exponentially distributed with some parameter $K_{xi} > 0$. This is consistent with the assumption of basin linearity. Then $f_{x1} * f_{x2} *\ldots* f_{xk}$ in Equation 6 becomes the k-fold convolution of independent but nonidentically distributed exponential random variables. That is,

$$f_{x1} * f_{x2} *\ldots* f_{xk}(t) = \sum_{i=1}^{k} C_{ik} \exp\left(-K_{xi} t\right) \tag{8}$$

where the coefficients C_{ik} are given by Feller (1971) as

$$C_{ik} = K_{x1} K_{x2} \ldots K_{xk-1} \left[\left(K_{x1} - K_{xi}\right) \cdot \left(K_{xi-1} - K_{xi}\right) \ldots \left(K_{xi+1} - K_{xi}\right) \ldots \left(K_{xk} - K_{xi}\right)\right]^{-1} \tag{9}$$

in which $K_{xi} \neq K_{xk}$ unless $i = k$. Therefore, the IUH is given as

$$h(t) = \sum_{s \varepsilon S} \sum_{i=1}^{k} C_{ik} \exp\left(-K_{xi} t\right) \cdot p(s), \tag{10}$$

$$s = \{x_1, x_2, \ldots, x_k\}$$

25. To apply Equation 10, the parameters K_{xi} must be determined. Following Gupta, Waymire, and Wang (1980), the mean holding time of an i^{th} order Strahler channel (state) is given by

$$\frac{1}{K_{ci}} = a\left(\bar{L}_i\right)^{1/3} , \quad 1 \leq i \leq W \tag{11}$$

where a is an empirical constant and $\bar{L}_i$ is the average channel length of order i , which can also be computed as

$$\bar{L}_i = \frac{1}{N_i} \sum_{j=1}^{N_i} L_{ji}, \quad i = 1, 2, \ldots, W \tag{12}$$

where N_i is the number of streams of order i and L_{ji} is the length of the j^{th} stream of order i . Likewise, the mean holding time $1/K_{ri}$ of an i^{th} order overland region can be given by

$$\frac{1}{K_{ri}} = a\left(\frac{A_{ri} A_w}{2N_i \bar{L}_i}\right)^{1/3} , \quad 1 \leq i \leq W \tag{13}$$

From a physical point of view, Equations 11 and 13 state that the mean holding time of a given state is proportional to some "characteristic length" of the state. The constant a is determined empirically and plausibly may remain more or less constant from one state to another within a given basin. Additional work will provide its range of variability on basins of diverse geomorphologic characteristics.

26. To use Equations 11 and 13, the constant a must be specified. The first moment of the IUH, $h(t)$, being equal to the mean holding time of the basin, K_B, can be written as

$$K_B = \int_0^{\infty} t\, h(t)\, dt \tag{14}$$

$$K_B = \left[\frac{\int_0^{\infty} t\, Q(t)\, dt}{\int_0^{\infty} Q(t)\, dt}\right] - \left[\frac{\int_0^{\infty} t\, I(t)\, dt}{\int_0^{\infty} I(t)\, dt}\right] \tag{15}$$

From Equations 10 and 14 it can be shown that

$$K_B = \sum_{s \epsilon S} p(s) \left(\frac{1}{K_{x1}} + \frac{1}{K_{x2}} + \ldots + \frac{1}{K_{xk}}\right), \tag{16}$$

$$s = \{x_1, x_2, x_3, \ldots, x_k\}$$

27. If Equations 11 and 13 are substituted into Equation 16, the only unknown is a. However, K_B is estimated following Boyd (1978) as

$$K_B = b\, A_W^{0.38} \tag{17}$$

where K_B is in hours and A_W is in square kilometres. The parameter b must be determined empirically. Thus, for a specified value of K_B, a can be determined. Methods for obtaining b are discussed later.

PART III: A QUASI-CONCEPTUAL LINEAR MODEL

28. The quasi-conceptual model based on drainage basin morphometry for direct runoff hydrograph synthesis (GMHS) consists of a number of subroutines, each describing a unique component. The arrangement of components, as shown in Figure 2, depends upon the need for optimization of model parameters. If optimization is not required, the components are: (1) MAIN, (2) BASIN, (3) LAG, (4) HOLD, (5) IUH, (6) PRECIP, (7) NEWTON, (8) INFIL, (9) XDATA, and (10) CONVOL. On the other hand, when optimization of parameters is required, components are (1) MAIN, (2) BASIN, (3) EXOP, (4) PRECIP, (5) NEWTON, (6) INFIL, (7) XDATA, (8) BROSEN, (9) OBJECT, (10) LAG, (11) HOLD, (12) IUH, and (13) CONVOL. A flowchart of the model is given in Figure 3, and its computer listing is provided in Appendix C. A brief discussion of the subroutines follows.

29. The component MAIN outputs general information on the GMHS model, initializes parameters, reads in and outputs the model objective, and specifies some inputs required by subroutines later. It also monitors whether optimization of model parameters is required. Put succinctly, MAIN sets the stage for the model and the tasks to be performed by it.

30. The rainfall-runoff data are processed by the subroutine PRECIP. These data are properly arranged, and their units specified. First, the rainfall data, which include values of rainfall intensity versus time, are read. Since time is read in clock-hours, it is reduced to a time series. Runoff data, which include values of discharge versus time, are then read. Here also, the time values are reduced to a time series. The runoff data represent direct runoff. If hydrograph separation needs to be performed for computation of the direct runoff, a separate subroutine must be provided for this purpose.

31. Effective rainfall and the portion of rainfall not contributing to direct runoff are computed by using subroutines INFIL and XDATA. The effective rainfall data are properly arranged. The time difference between the start of the effective rainfall and that of the direct runoff is noted. Infiltration capacity is computed as a function of time using the Philip two-term infiltration model (Philip 1969). If the infiltration capacity is to be computed by another method, INFIL must be modified accordingly. The infiltration model has two parameters: (a) sorptivity accounting for capillary effects and (b) saturated hydraulic conductivity accounting for gravity

effects. These parameters are computed in an iterative manner based on Newton's method with the subroutine NEWTON. It is assumed that sorptivity is subject to change from one rainfall-runoff event to another on the same basin; on the other hand, saturated hydraulic conductivity remains fixed for a basin but may differ from one basin to another.

32. The basin characteristics are analyzed by the subroutine BASIN. The principal geomorphologic characteristics are (a) basin area, (b) areas of overland regions, (c) channel lengths, and (d) number of channels of each order. This subroutine is used to calculate mean channel lengths $\bar{L}_i$ and areas of overland regions for each order. Basin lag is computed using basin area in association with Equation 17 by the subroutine LAG. If a different method is to be used for computing basin lag, this subroutine must be modified accordingly.

33. The mean holding times of overland flow and channel flow are computed by the subroutine HOLD, using Equations 11 and 13 and the basin characteristics given by the subroutine BASIN. The instantaneous unit hydrograph is computed by the subroutine IUH using Equations 9 and 10. To obtain the direct runoff hydrograph, the IUH is then convoluted with the effective rainfall obtained from the subroutine PRECIP by the subroutine CONVOL, which also compares computed direct runoff hydrographs with the corresponding observed direct runoff hydrographs.

34. When optimization of parameters is needed, then some additional components are used as shown in Figure 2. The subroutine EXOP provides pertinent information required by the optimization algorithm, including specification of initial guesses, upper and lower bounds on parameter values, number of stage searches, and convergence limit.

35. The subroutine OBJECT specifies the objective function to be used in optimization of model parameters. The objective function was defined as the sum of squares of deviations between observed and computed discharge peaks and their times of occurrences. A weighting factor was used to assign relative weights to the two components of the objective function. Not more than 20-percent weight was allocated to the component based on the sum of squares of deviations between observed and computed peak times.

36. Optimization of parameters is performed by the subroutine BROSEN, which combines the original Rosenbrock method (Rosenbrock 1960), the Palmer version (Palmer 1969), and the penalty function method. The problem of

optimization is formulated as a constrained minimization problem requiring the vector always to be an interior point of the feasible set. The subroutines EXOP and OBJECT provide pertinent information to initiate optimization.

PART IV: APPLICATION TO NATURAL WATERSHEDS

37. The quasi-conceptual linear model presented previously was verified on five small experimental agricultural watersheds designated as C, D, G, Y, and 2-H. These watersheds range in area from 0.0137 to 17.72 km^2. The availability of rainfall, runoff, and geomorphic data was the primary consideration for their selection. The geographic locations of these watersheds are shown in Figure 4. Watersheds C, D, and G are shown in Figure 5, while watersheds Y and 2-H are shown in Figures 6 and 7, respectively.

Description of Watersheds

Watershed C

38. Watershed C is located near Riesel, TX. As shown in Figure 8, it is a second-order watershed having an area of 2.343 km^2. Its tree-structure is shown in Figure 9. Its drainage network properties are abstracted from the topographic map. The order of channel network, number of channel elements of each order, and length and area of each channel element are given in Table 1.

Watershed D

39. Watershed D, shown in Figure 10, includes watershed C. Located near Riesel, TX, it has an area of 4.492 km^2. It is a second-order watershed having a tree-structure as shown in Figure 11. Its drainage network properties are shown in Table 2.

Watershed G

40. Watershed G, located near Riesel, TX, includes watersheds C and D. It has a total area of 17.72 km^2, as shown in Figure 12. This is a fourth-order watershed, as shown in Figure 13. Its drainage network properties are given in Table 3.

Watershed Y

41. Watershed Y, shown in Figure 14, is located near Riesel, TX, and has an area of 1.251 km^2. This is a third-order watershed, as shown in Figure 15. Its drainage network properties are presented in Table 4.

Watershed 2-H

42. Located near Hastings, NE, Watershed 2-H is the smallest of all watersheds considered in this study. As shown in Figure 16, it has an area of 0.0137 km^2. It consists of three channel elements as shown in Figure 17.

Table 1

Drainage Network Properties of Watershed C, Riesel, TX

(Watershed Area = 2.343 km^2)

Serial Number	Channel Length		Contributing Area	
	km	ft	km^2	acres
		Order 1		
1	1.295	4,250	0.833	205.91
2	0.647	2,125	0.232	57.40
3	0.610	2,000	0.272	67.19
4	0.687	2,255	0.257	63.46
5	0.555	1,820	0.230	56.82
		Order 2		
1	0.882	2,895	0.519	128.22

Table 2

Drainage Network Properties of Watershed D, Riesel, TX

(Watershed Area = 4.492 km^2)

Serial Number	Channel Length		Contributing Area	
	km	ft	km^2	acres
		Order 1		
1	1.295	4,250	0.833	205.91
2	0.647	2,125	0.232	57.40
3	0.609	2,000	0.272	67.19
4	0.687	2,255	0.257	63.46
5	0.554	1,820	0.230	56.82
6	1.143	3,750	0.426	105.40
7	1.256	4,120	0.450	111.25
8	0.838	2,750	0.624	154.32
9	0.480	1,575	0.132	32.51
		Order 2		
1	2.108	4,940	1.006	168.66
		1,975		80.11

Table 3

Drainage Network Properties of Watershed G, Riesel, TX

(Watershed Area = 17.72 km^2)

Serial Number	Channel Length		Contributing Area	
	km	ft	km^2	acres
		Order 1		
1	0.765	2,510	0.646	159.72
2	1.753	5,750	0.989	244.40
3	1.4478	4,750	0.620	153.30
4	2.118	6,950	1.083	267.64
5	0.363	1,190	0.189	46.92
6	0.399	1,310	0.101	24.96
7	1.0866	3,565	0.757	187.05
8	1.256	4,120	0.450	111.25
9	1.143	3,750	0.426	105.40
10	0.555	1,820	0.230	56.82
11	0.687	2,255	0.257	63.46
12	1.295	4,250	0.833	205.91
13	0.648	2,125	0.232	57.40
14	0.610	2,000	0.272	67.19
15	0.838	2,750	0.624	154.32
16	0.480	1,575	0.132	32.51
17	0.777	2,550	0.474	117.21
18	0.686	2,250	0.779	192.53
19	0.533	1,750	0.233	57.51
20	0.3429	1,125	0.097	23.95
21	1.067	3,500	0.625	154.42
22	0.839	2,755	39.15	96.73
23	0.570	1,870	0.310	76.52
24	0.419	1,375	0.116	28.72
25	0.968	3,175	0.528	130.51
26	1.343	4,405	0.680	168.00
		Order 2		
1	0.917	3,010	0.334	82.53
2	3.216	10,550	1.396	345.06
3	0.326	1,070	0.077	19.12
4	0.954	3,130	0.512	126.60
5	1.646	5,400	0.698	172.53
		Order 3		
1	3.394	11,136	2.521	623.02
2	0.155	510	0.077	19.14
		Order 4		
1	0.107	350	0.029	7.31

Table 4

Drainage Network Properties of Watershed Y, Riesel, TX

(Watershed Area = 1.251 km^2)

Serial Number	Channel Length		Contributing Area	
	km	ft	km^2	acres
		Order 1		
1	0.395	1,300	0.282	69.655
2	0.097	1,450	0.097	23.938
3	0.332	1,090	0.152	37.673
4	0.094	310	0.094	23.349
5	0.137	450	0.122	30.020
		Order 2		
1	0.296	970	0.112	27.606
2	0.543	1,780	0.216	50.819
		Order 3		
1	0.259	850	0.2	41.211

This is a second order watershed. Its drainage network properties are given in Table 5.

Table 5

Drainage Network Properties of Watershed 2-H, Hastings, NE (Watershed Area = 0.0137 km^2)

Serial Number	Channel Length		Contributing Area	
	km	ft	km^2	acres
		Order 1		
1	0.0219	72	5.79×10^{-3}	1.4298
2	0.015	4	0.001	0.2468
		Order 2		
1	0.062	204	0.007	1.7217

Rainfall-Runoff Data

43. Rainfall-runoff data for each watershed were obtained from the US Department of Agriculture publications entitled, "Hydrologic Data for Experimental Agricultural Watersheds in the United States." These publications contain the largest yearly flood events, between 8 and 10 for each watershed. These events were divided into two mutually exclusive groups, one for optimization of model parameters and the other for model verification. Numbers of events available for each basin and used for model calibration and verification are as follows:

	Number of Rainfall-Runoff Events		
Watershed	Available for Analysis	Used for Calibration	Used for Verification
C	9	5	4
D	8	4	4
G	8	4	4
Y	8	4	4
2-H	10	5	5

For each rainfall-runoff event, direct runoff was obtained by hydrograph separation.

Determination of Infiltration

44. Infiltration for each rainfall-runoff event was determined on each watershed by using the Philip two-term infiltration model (Philip 1969),

$$f = A + 0.5\ St^{-0.5} \tag{18}$$

where

f = rate of infiltration (cm/hr) at time t

A = parameter approximately equal to saturated hydraulic conductivity (cm/hr)

S = parameter called sorptivity (cm/hr$^{0.5}$)

The parameter A depends mainly on the soil type and was therefore fixed for a given basin. Values used were as follows:

Watershed	Value of A, cm/hr
C	0.254
D	0.254
G	0.254
Y	0.254
2-H	0.508

The parameter S depends on antecedent soil moisture and other physical characteristics. It was determined for each rainfall-runoff event on each basin by a volume balance analysis. Its determination on an ungaged basin remains an unsolved problem.

Parameter Estimation

45. The GMHS has only one unknown parameter in Equation 17. This parameter b was determined for each basin by using a modified Rosenbrock-Palmer optimization algorithm (Rosenbrock 1960, Palmer 1969). The values for the various basins were as follows:

Watershed	Value of b, cm/hr
C	0.875
D	0.875
G	1.2734
Y	0.875
2-H	0.875

Instantaneous Unit Hydrograph

46. Using these parameter values, the IUH was determined for each watershed; the IUHs are shown in Figures 18-22. It is apparent that the IUHs possess appropriate shape characteristics. For very small watersheds, C for example (Figure 18), the IUH experiences a quick rise and a quick recession. As the area increases, the rates of rise and recession become more moderate as can be observed for watershed G (Figure 20).

Runoff Prediction

47. The runoff hydrograph was predicted for each event in the prediction set using the parameter b, estimated in the manner set forth in paragraph 44. Comparisons of observed and predicted runoff hydrographs for sample events on each watershed are shown in Figures 23-27. The predicted hydrographs compare reasonably well with observed hydrographs with regard to shape, time of rise, time of recession, and peak characteristics. The prediction error in peak discharge and time to peak is as high as 50 percent; in most cases, though, it is considerably less. Two factors are worthy of note here. First, antecedent moisture conditions are extremely important. The infiltration parameter S and the effective rainfall pattern are very sensitive to the antecedent moisture condition and, as a consequence, so is the runoff hydrograph. A small change in the effective rainfall pattern results in a marked difference in runoff hydrograph characteristics. Second, the parameter b, although determined optimally, may not have represented the range of conditions persisting on a given watershed over a long period of time. This is due to a relatively small number of events being available for its estimation. The runoff hydrograph is quite sensitive to b since this is the only parameter in the IUH. Nevertheless, given model simplicity and its basis in drainage network morphometry, the prediction results are encouraging. Additional model testing needs to be done for more definitive conclusions.

Considerations of Basin Size

48. Although the GMHS has been applied to five small gaged basins, its application is by no means confined to small basins. Large basins have pronounced variability in rainfall distribution, infiltration rate, and surficial characteristics, all of which need to be accounted for in the model. There are two ways to handle this problem. First, the entire basin may be considered one unit, regardless of how heterogeneous it is. The basin is represented by a number of paths, each having an associated area corresponding to an ensemble of the portions of basin area draining into this path. Because these portions are of a heterogeneous nature, hydrologic variables can be averaged. For example, a certain path drains some of the overland regions of first order. Rain falling on these regions can be proportioned by their

respective areas, and the same can be done for infiltration and other variables.

49. Second, a large basin can be divided such that each subbasin can be considered a homogeneous unit. The model can then be applied to each subbasin, and outputs of the subbasins properly routed to produce the direct runoff hydrograph of the entire basin. Therefore, the size of the basin does not appear to be a limitation on model applicability.

PART V: CONCLUSIONS

50. The following conclusions are drawn from this study:

a. The IUH determined by the model appears to possess appropriate hydrologic properties. From those generated and examined in this study, it is apparent that they possess appropriate shape characteristics. For very small watersheds, the IUH experiences a quick rise and a quick recession. As the area increases, however, the rates of rise and recession become more moderate.

b. The runoff hydrographs predicted by the model compare reasonably well with observed hydrographs with reference to shape, time of rise, time of recession, and peak characteristics. The prediction error in peak discharge and time to peak was as high as 50 percent; in most cases, though, it was considerably less than 30 percent.

c. Antecedent soil moisture and infiltration are extremely important for accurate model predictions. The infiltration parameter S and the effective rainfall pattern are very sensitive to antecedent moisture conditions and, as a consequence, so is the runoff hydrograph. A small change in the effective rainfall pattern makes a material difference in the characteristics of a predicted runoff hydrograph. The runoff hydrograph is quite sensitive to b since this is the only parameter in the IUH. The parameter b, although determined optimally in this study, was probably not representative of the range of conditions that persisted on a given watershed over a long period of time because of a small number of events available for its estimation.

d. The b parameter appearing in the lag-area relation, Equation 17, needs further scrutiny. This parameter should be related to some physical basin characteristic.

e. The GMHS model is partially based on drainage network properties. This feature suggests that the model should be applicable to ungaged basins. However, additional model testing will be needed to make more definitive inferences.

PART VI: RECOMMENDATIONS

51. This report represents a portion of a larger effort, i.e. the simulation of streamflow for ungaged basins. Much additional work is needed. Some fruitful areas of research are as follows:

a. Determination of the volume of direct runoff resulting from a specified rainfall event is essential for subsequent synthesis of its associated direct runoff hydrograph. Current procedures for computing this volume are inadequate and usually are not applicable to ungaged basins. Despite its crucial importance in streamflow simulation, this aspect has not been addressed adequately in hydrologic literature.

b. A study to relate the b parameter in Equation 17 to measurable basin characteristics is required. This is essential if geomorphologic approaches are to be used to synthesize the IUH for ungaged basins.

c. Evaluating the effect of basin size and its ordering on the IUH is important from a practical standpoint. The detail required for describing a drainage network should be determined for the model reported here. For example, is it necessary to represent a sixth-order basin as it is, or will scaling down to fourth-order representation suffice?

d. The effects of spatial distribution of rainfall on generation of direct runoff are not completely known. This is an important aspect of streamflow forecasting and deserves considerable attention.

e. The sensitivity of the GHMS model to various kinds of errors in its parameters and inputs needs to be determined. This is necessary to decide whether the model is adequate, requires improvement, or can be further simplified without significant loss of accuracy.

f. For the model to be applicable to ungaged basins, each of its components needs to be related to measurable basin characteristics. Parameters of the infiltration model might be estimated in this manner.

g. A better assessment of the accuracy and reliability of this model is needed. The level of confidence that can be placed on model results is not clear.

h. The GHMS model should be compared with others on the basis of drainage network characteristics. Results of such an effort will allow for placing the model in its proper perspective, especially in relation to others.

i. Based on applications made to date, i.e. to small basins, the GHMS model is best interpreted mathematically in terms of the standard hydrologic concept of storage elements. In the future, though, when applied at the subbasin level where routing becomes an integral part of the overall procedure, the

GHMS should be interpreted mathematically as representing a network of storage elements and channels.

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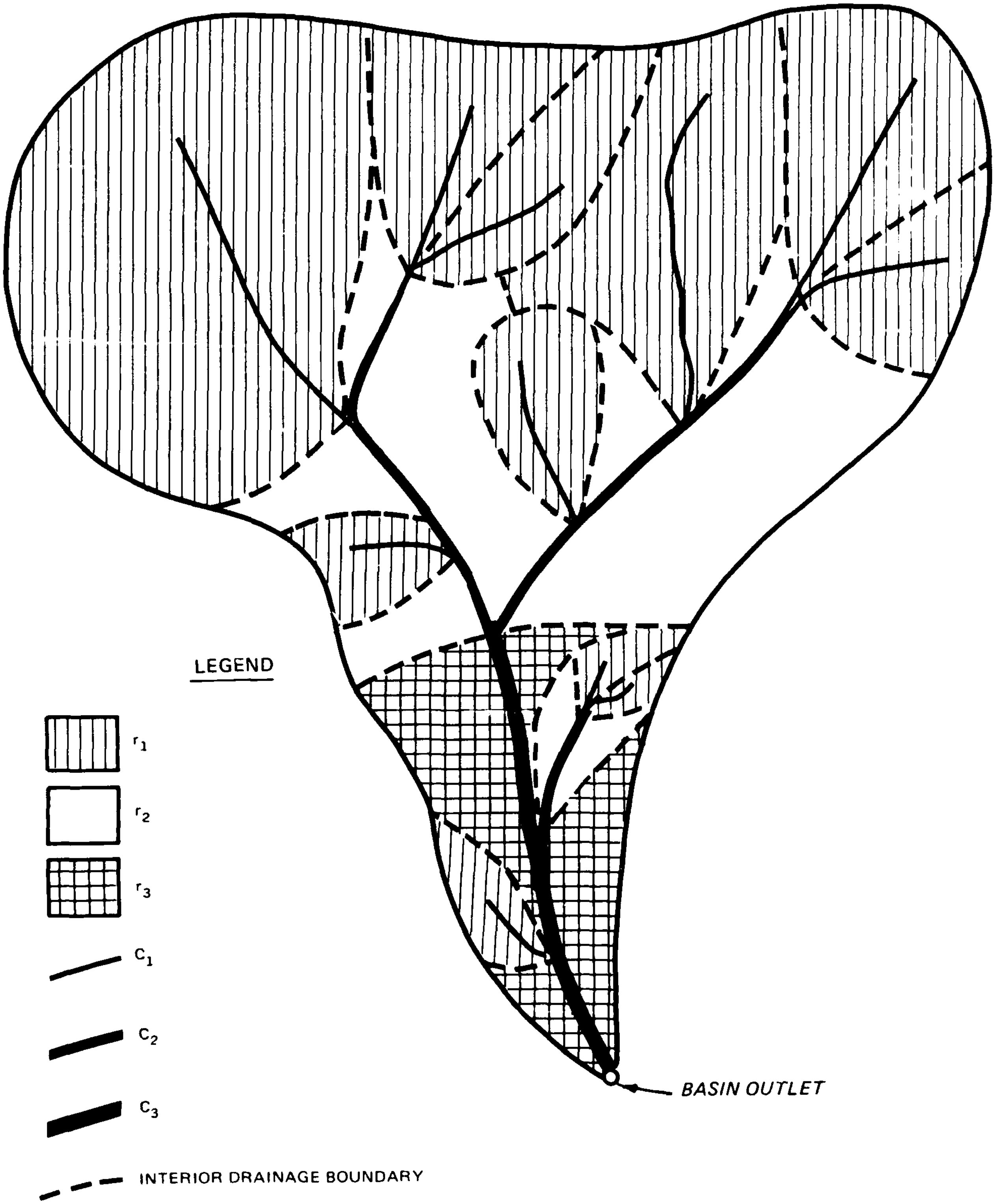

Figure 1. A hypothetical third-order watershed with Strahler ordering system

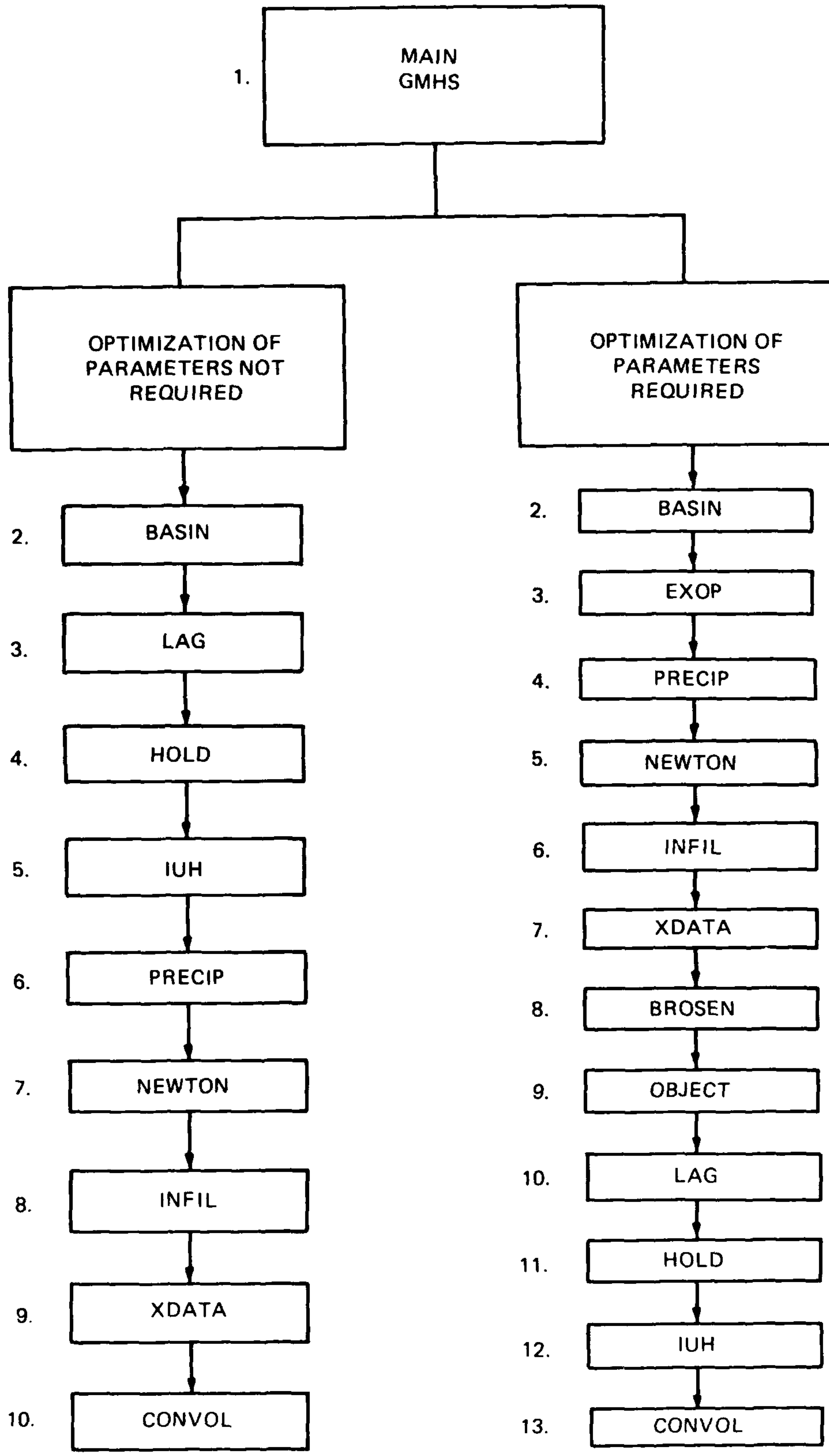

Figure 2. Components of the hydrograph synthesis model GMHS

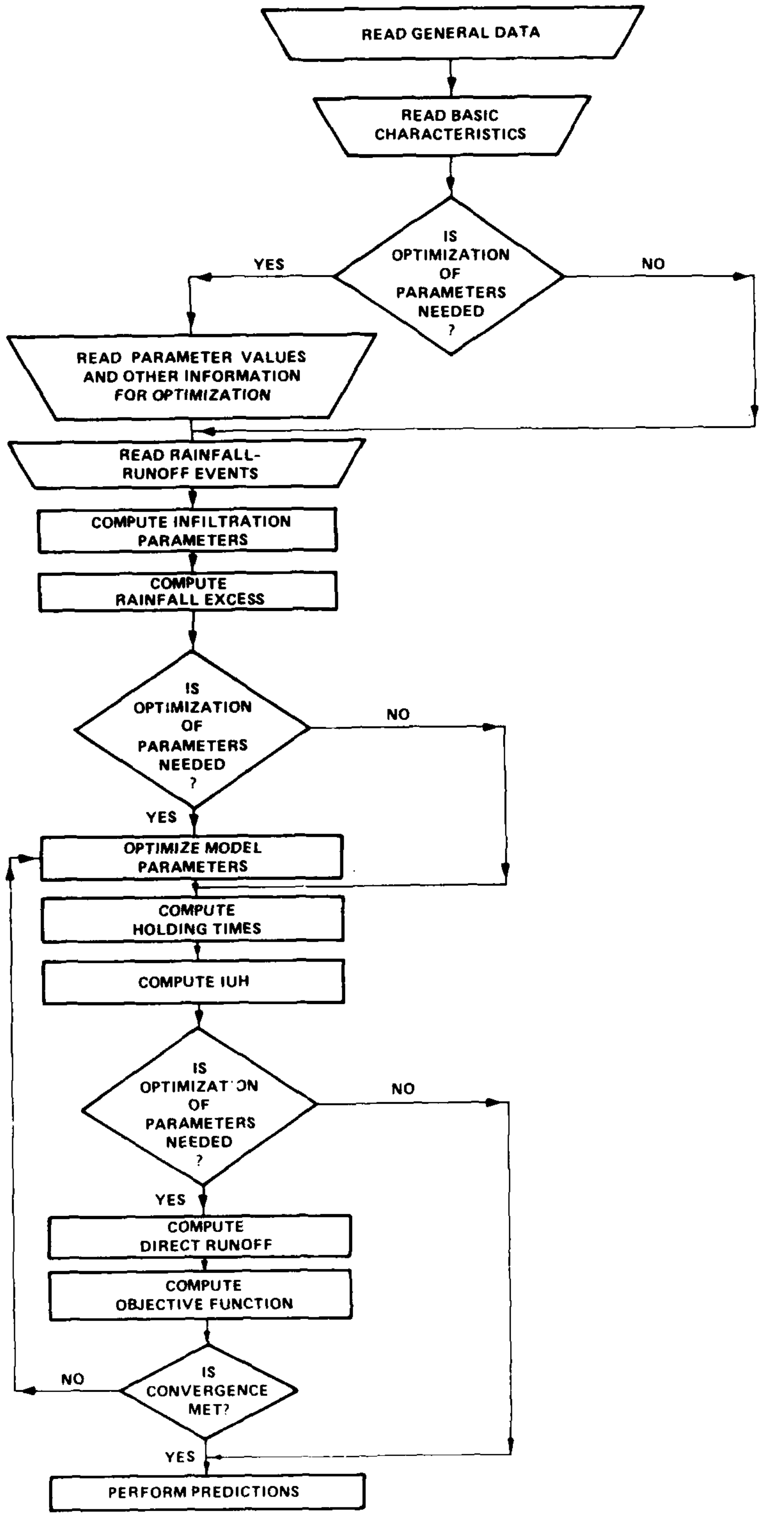

Figure 3. Computer flowchart of the GMHS model

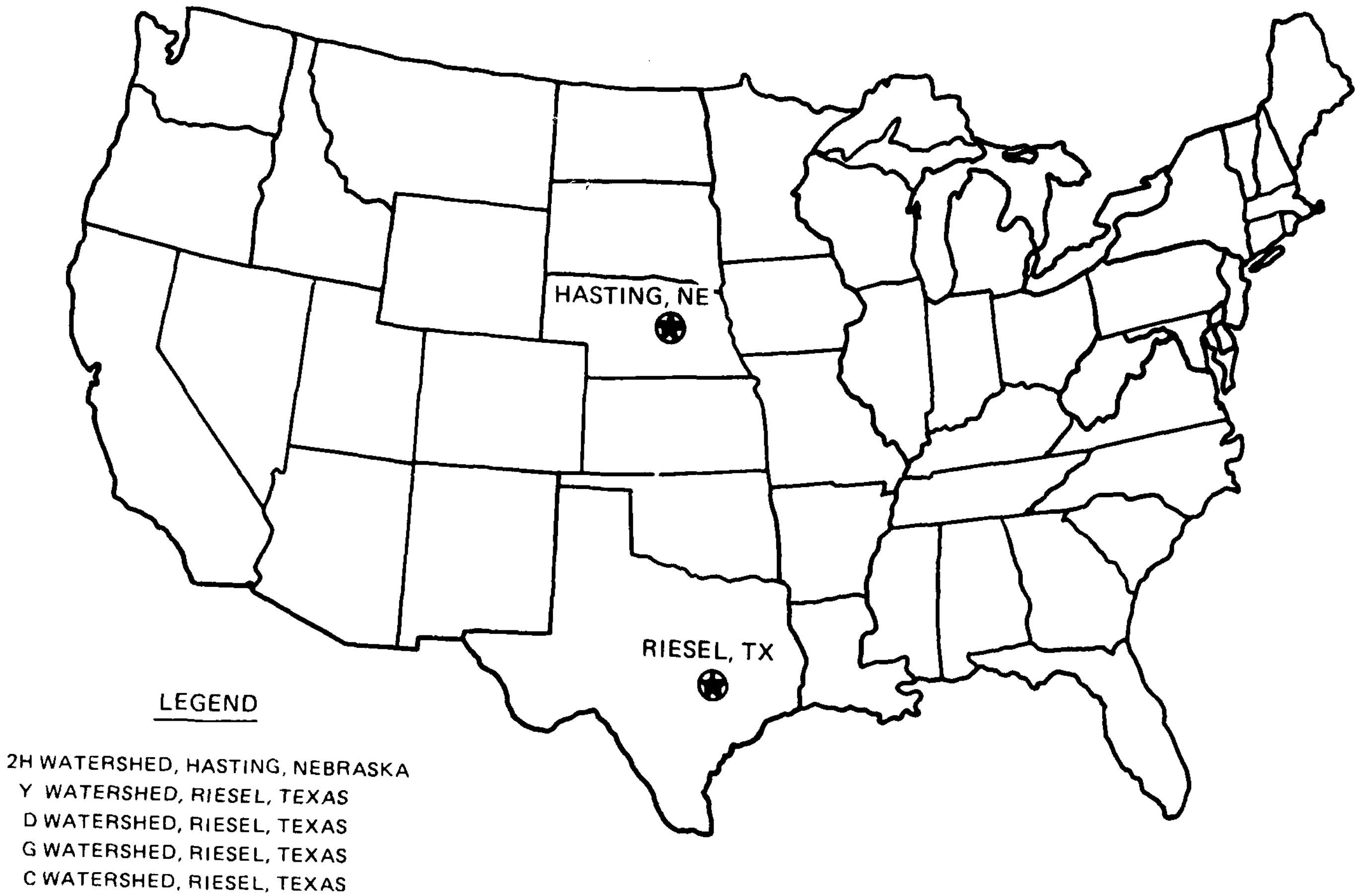

Figure 4. Location of watersheds

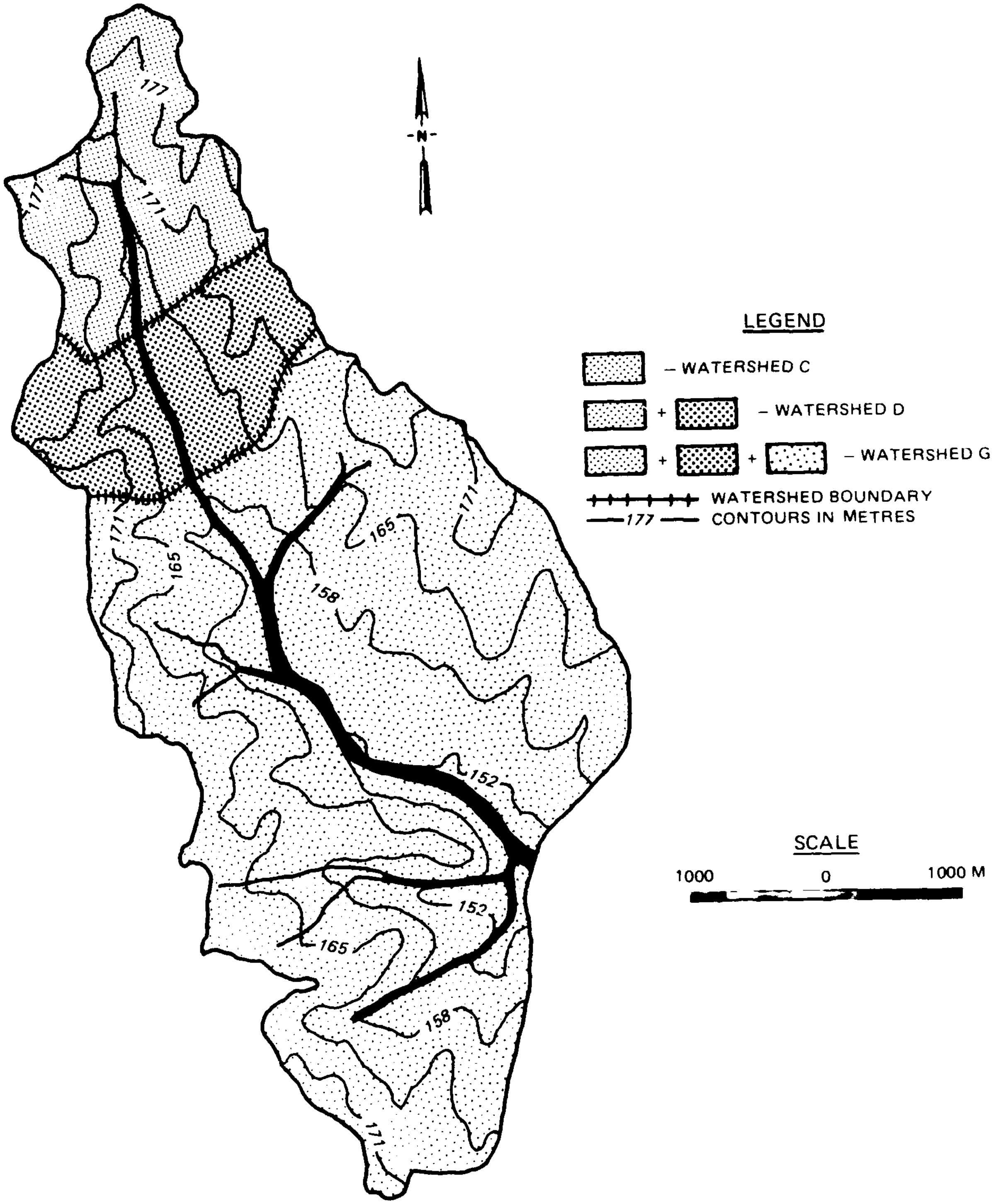

Figure 5. Watersheds C, D, and G near Riesel, TX

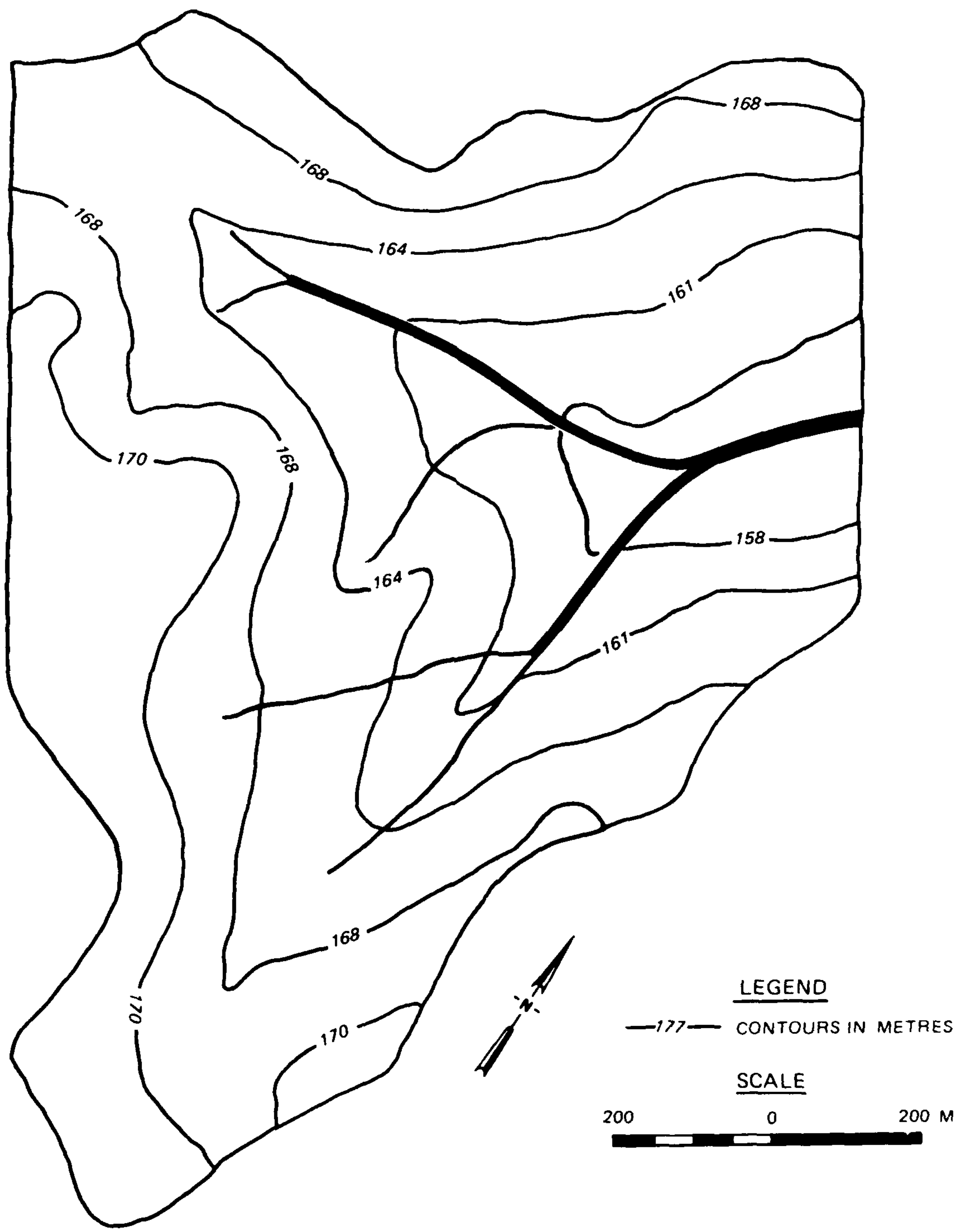

Figure 6. Watershed Y near Riesel, TX

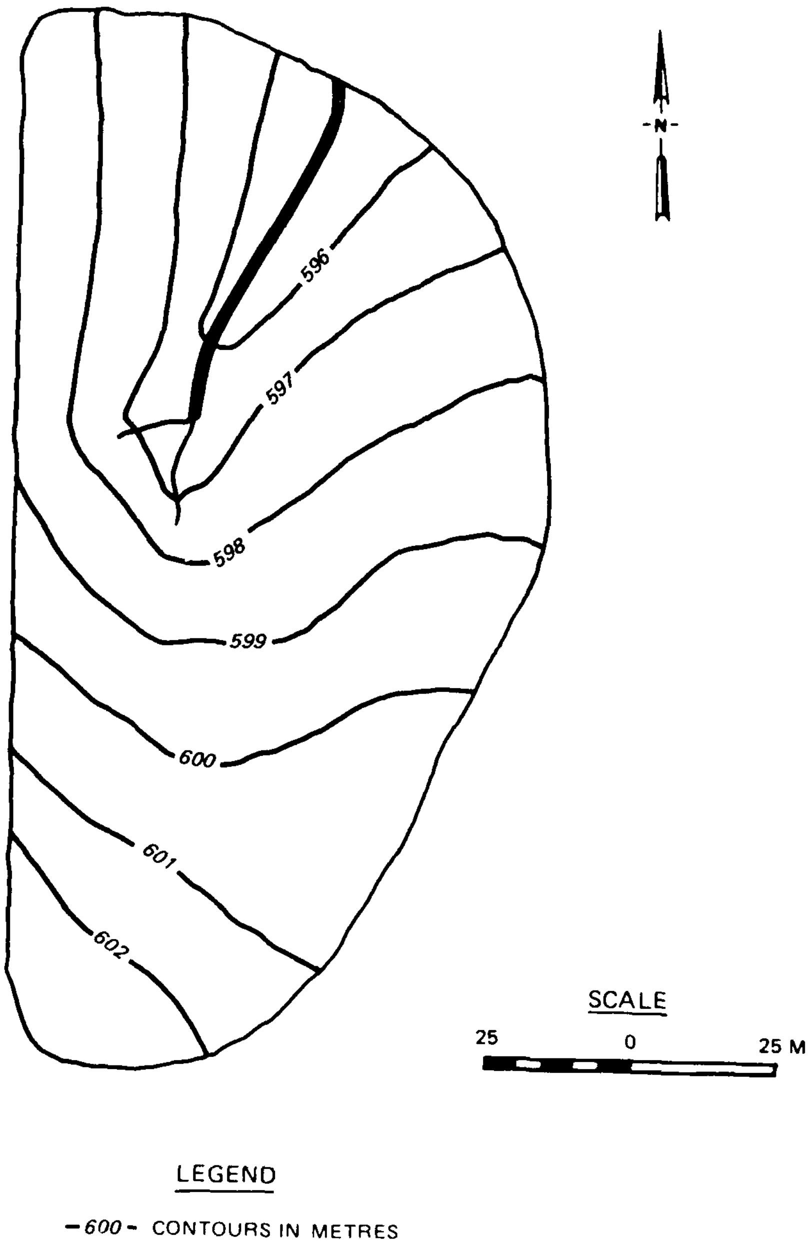

Figure 7. Watershed 2-H near Hastings, NE

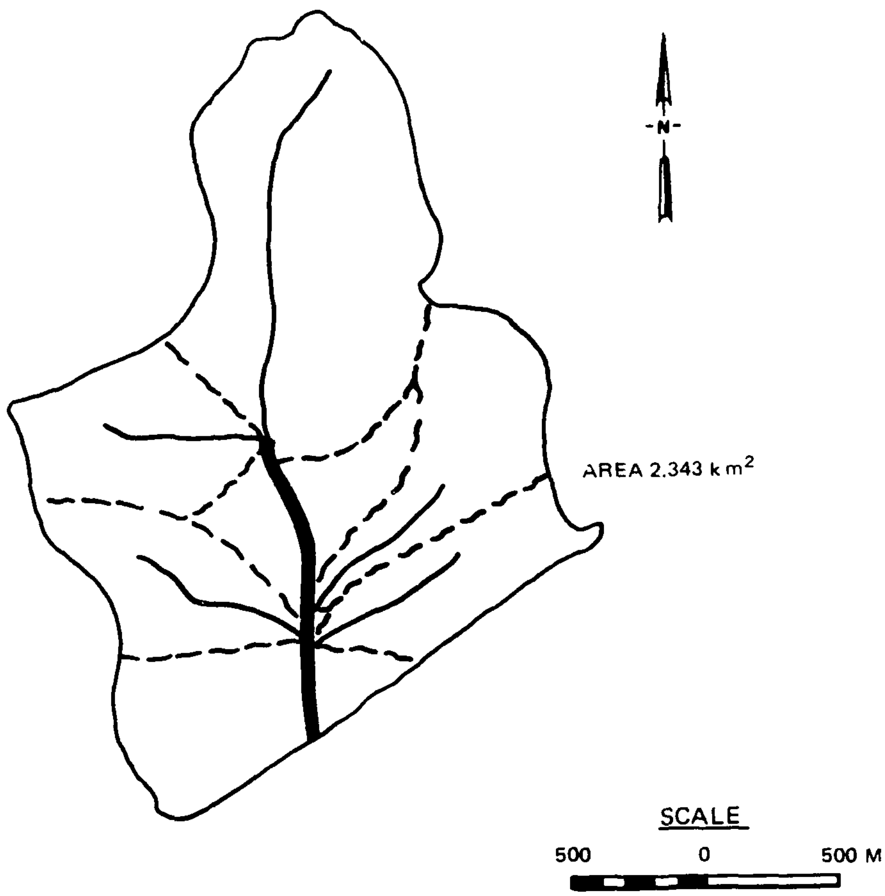

Figure 8. Watershed C, Riesel, TX

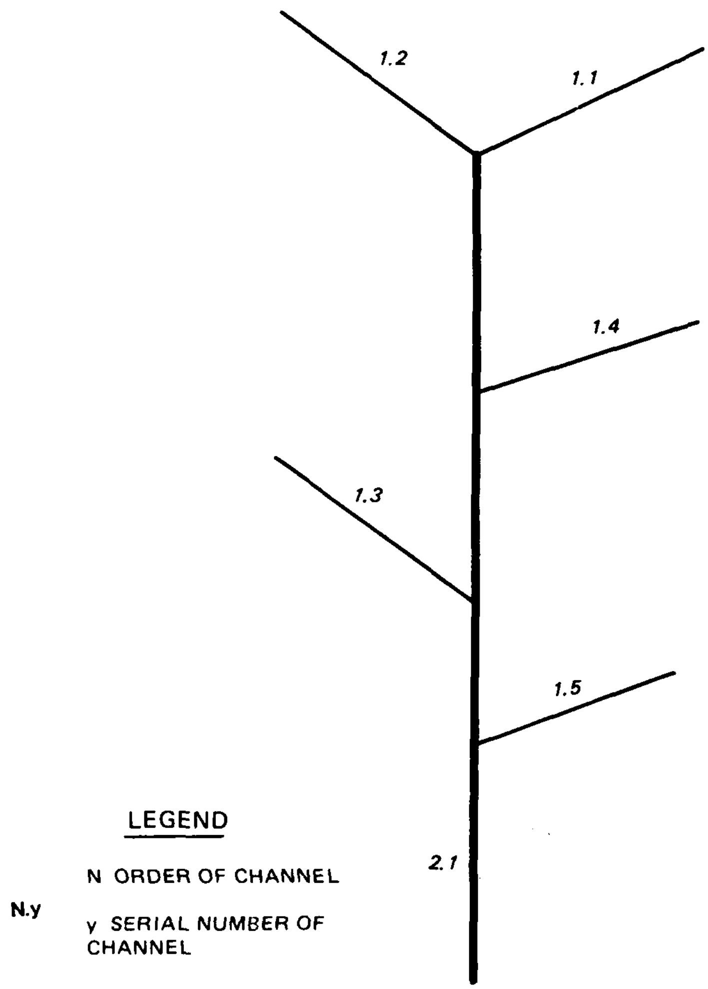

Figure 9. Tree structure of watershed C, Riesel, TX

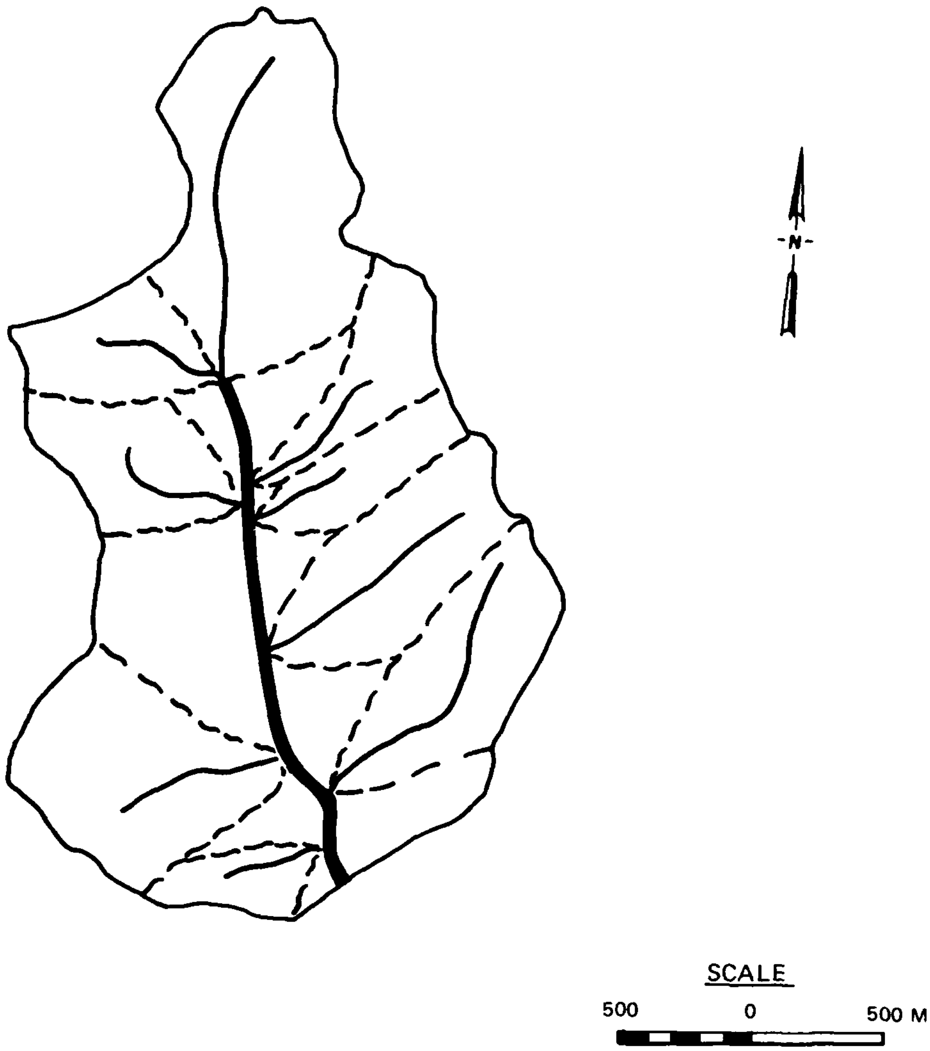

Figure 10. Watershed D, Riesel, TX

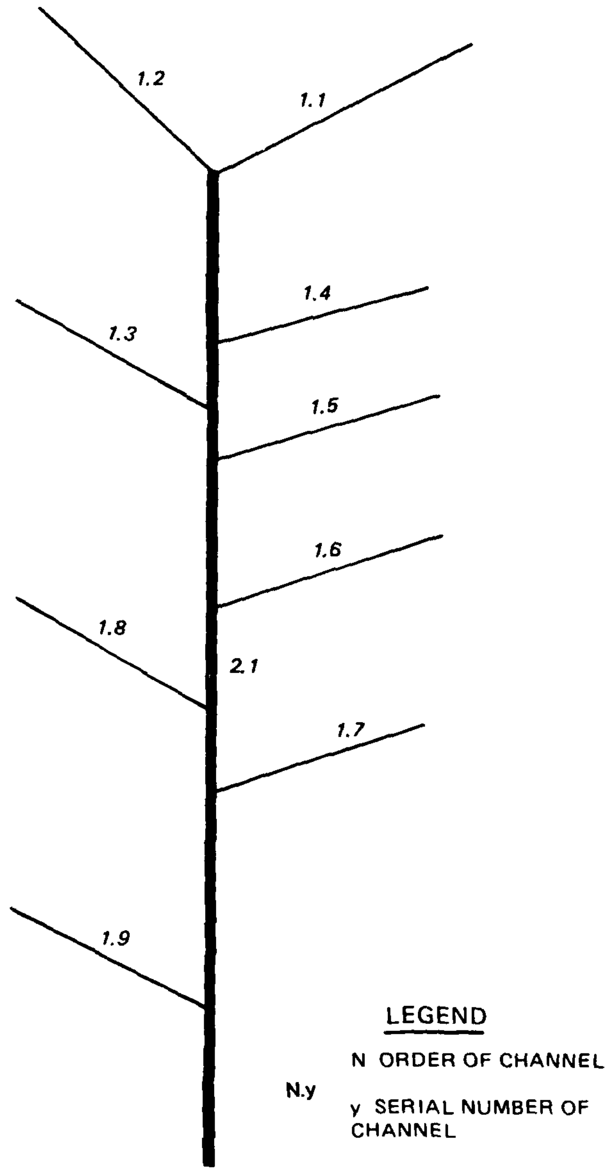

Figure 11. Tree structure of watershed D, Riesel, TX

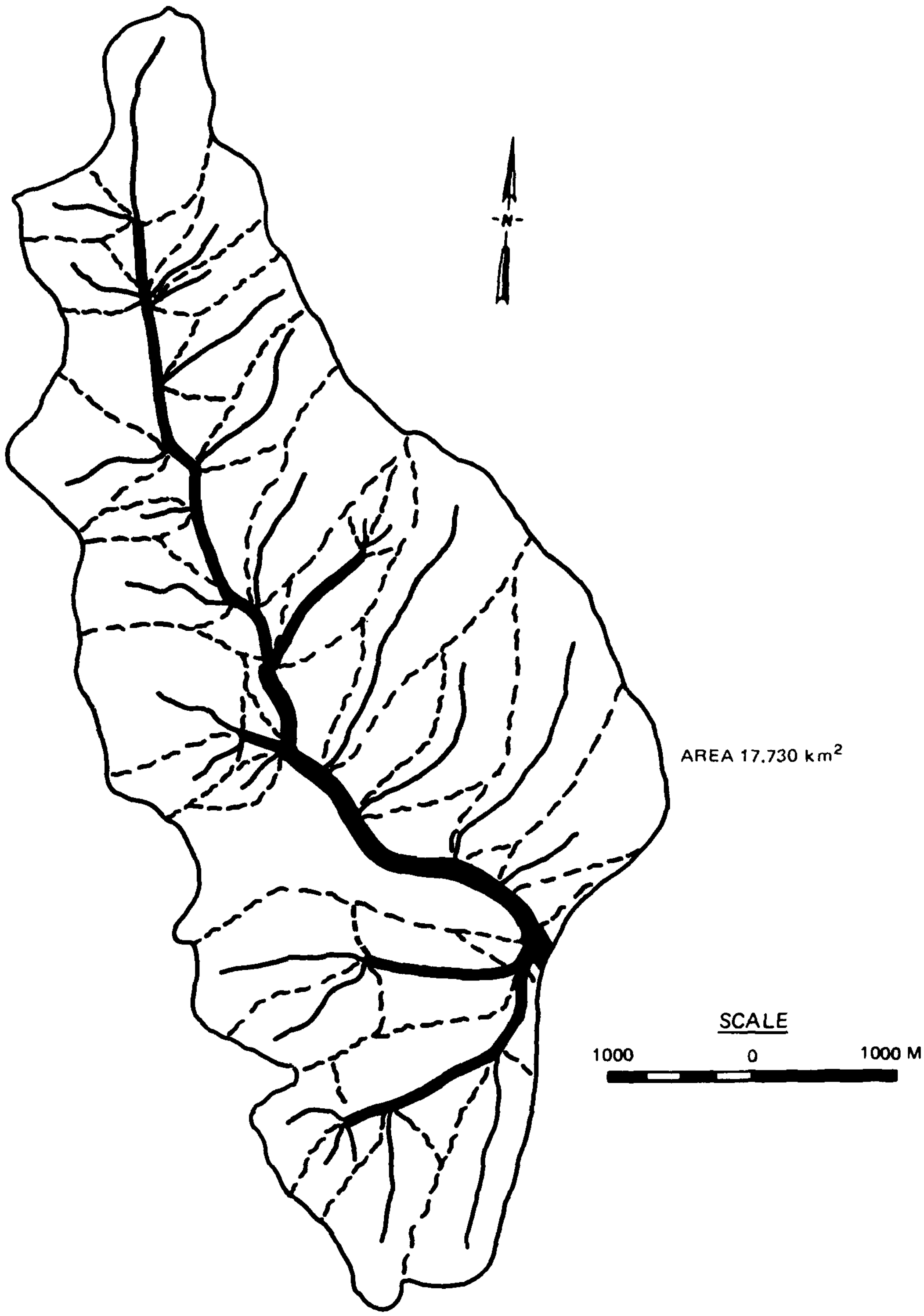

Figure 12. Watershed G, Riesel, TX

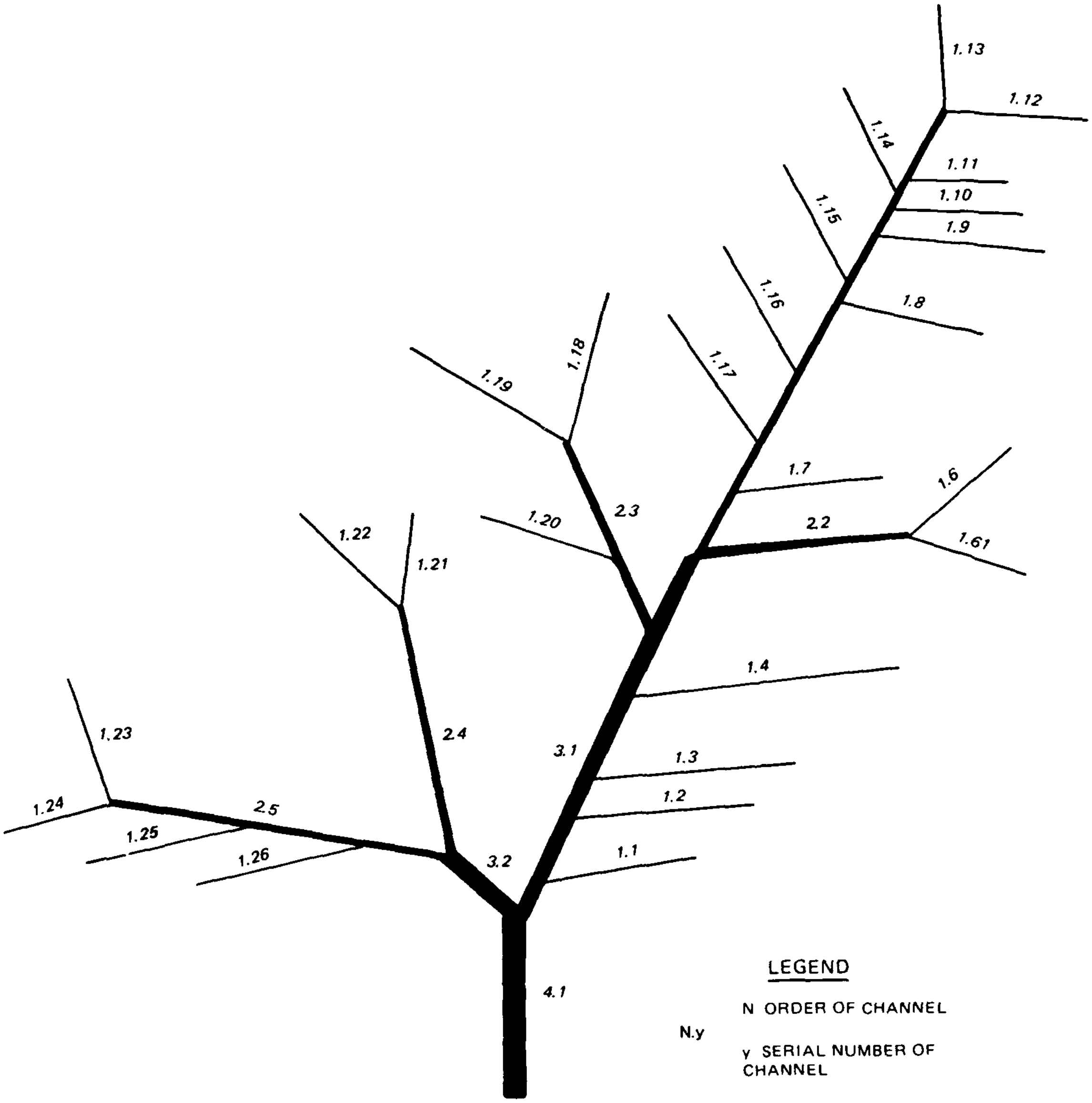

Figure 13. Tree structure of watershed G, Riesel, TX

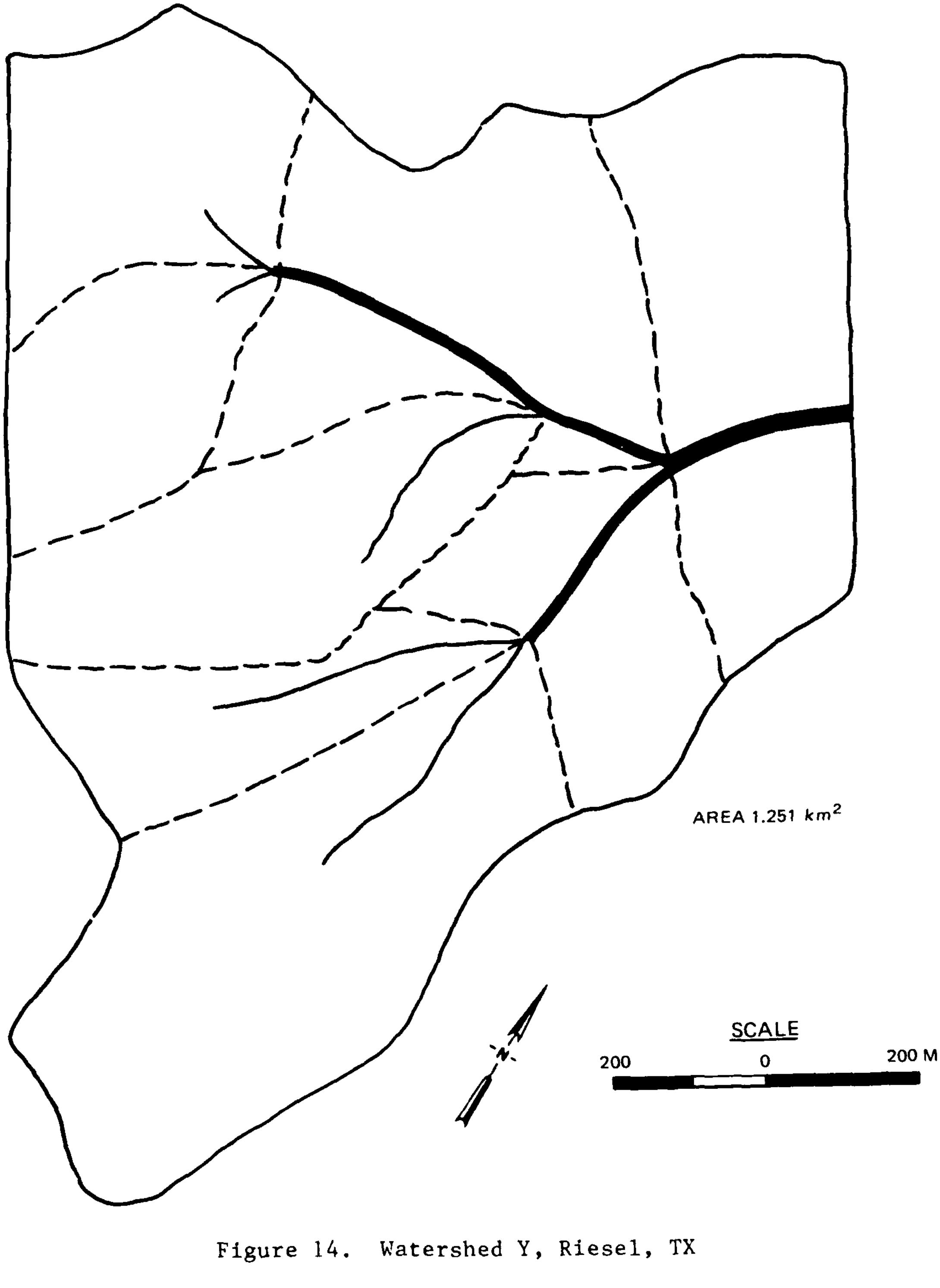

Figure 14. Watershed Y, Riesel, TX

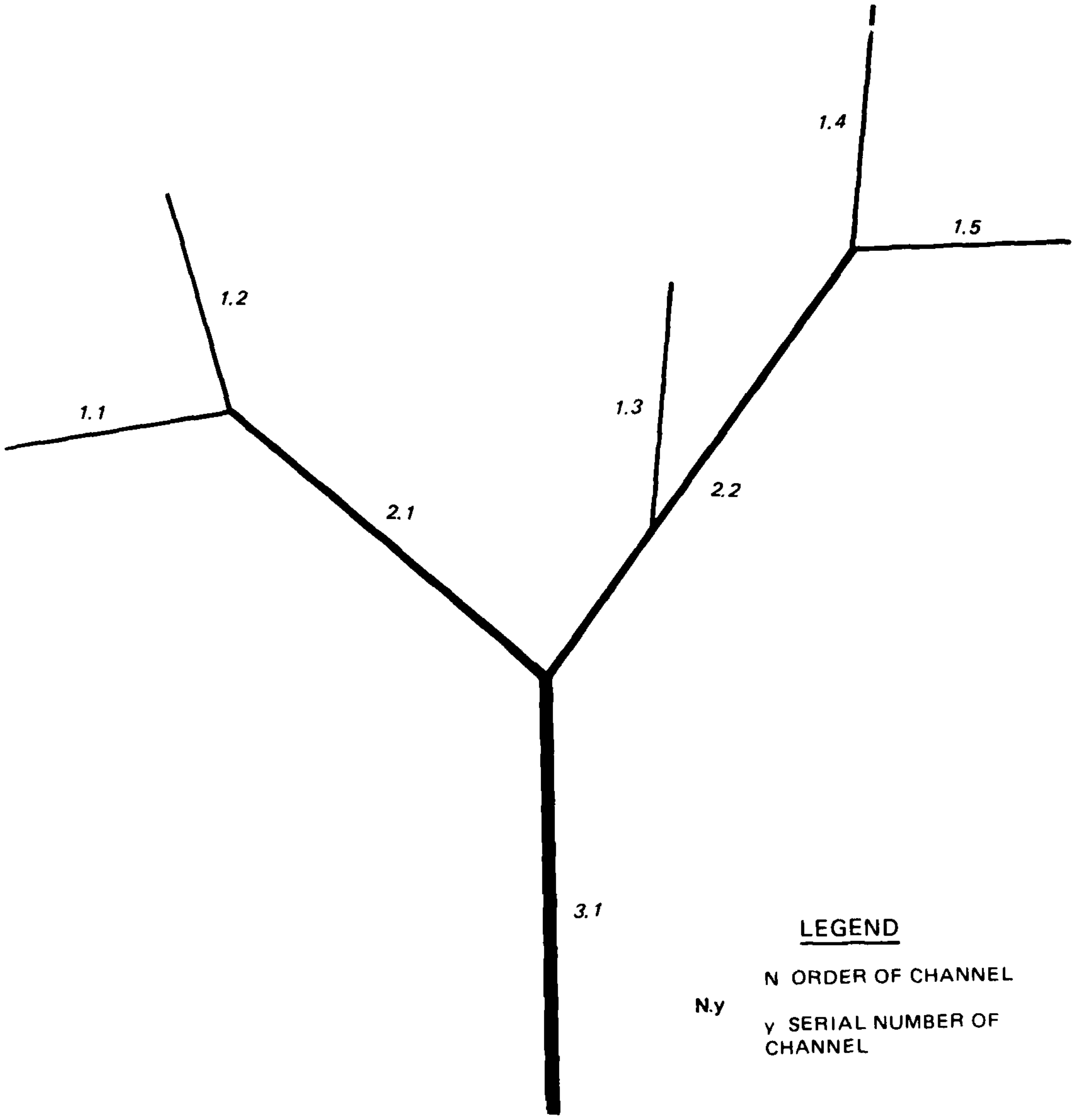

Figure 15. Tree structure of watershed Y, Riesel, TX

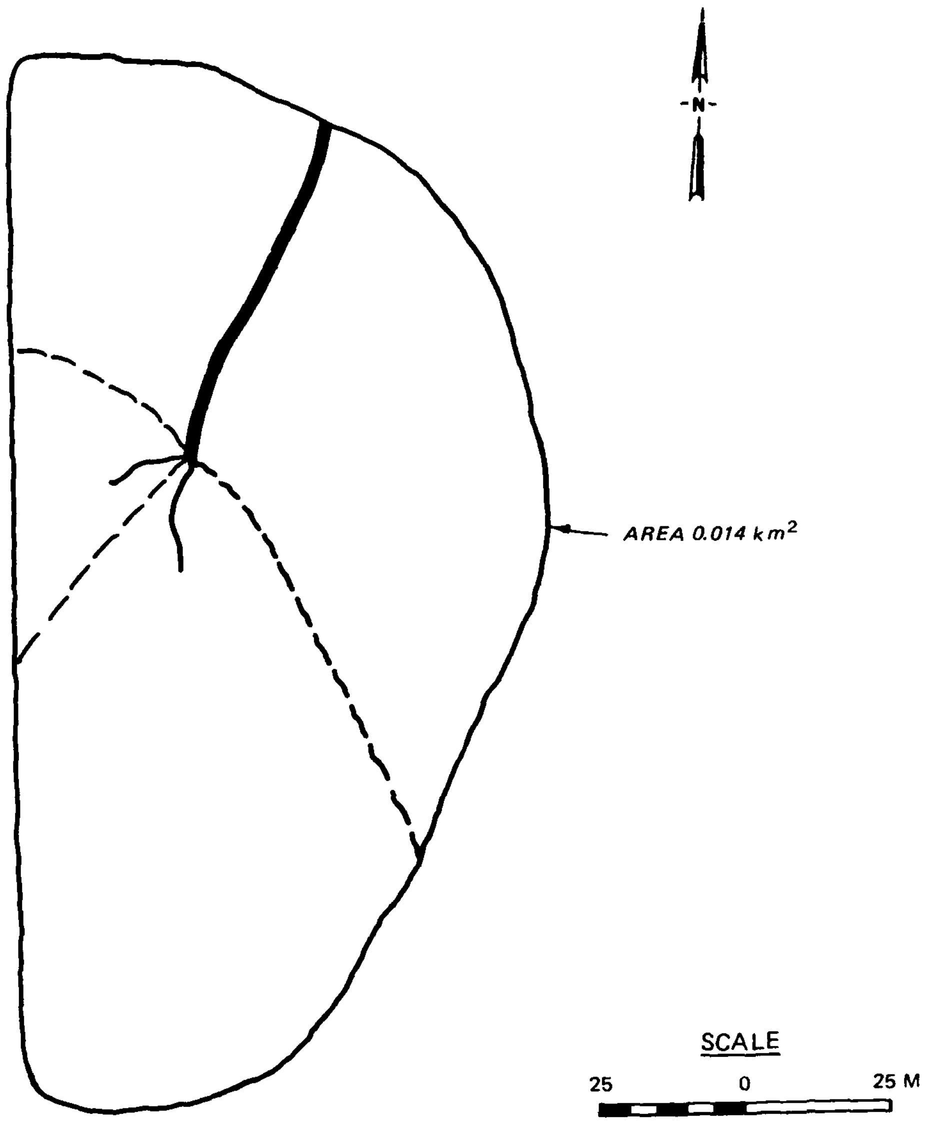

Figure 16. Watershed 2-H, Hastings, NE

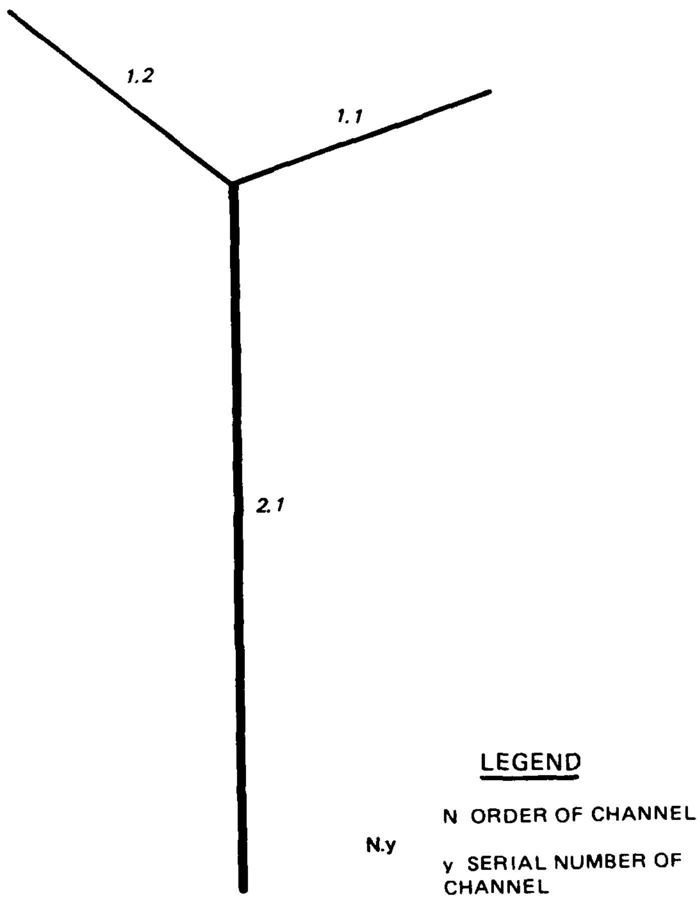

Figure 17. Tree structure of watershed 2-H, Hastings, NE

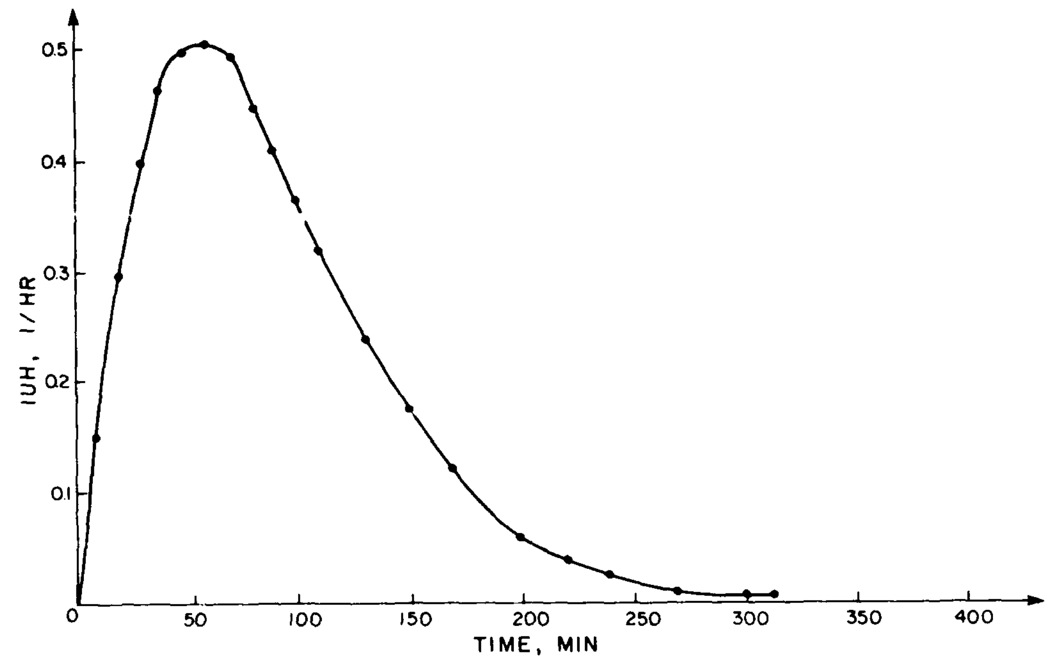

Figure 18. The instantaneous unit hydrograph of watershed C, Riesel, TX

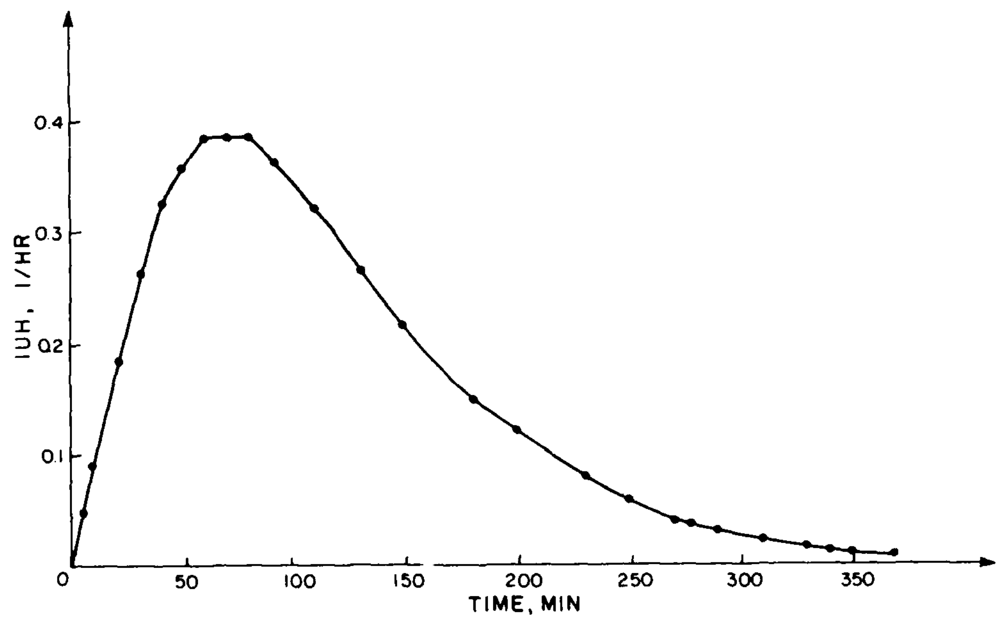

Figure 19. The instantaneous unit hydrograph of watershed D, Riesel, TX

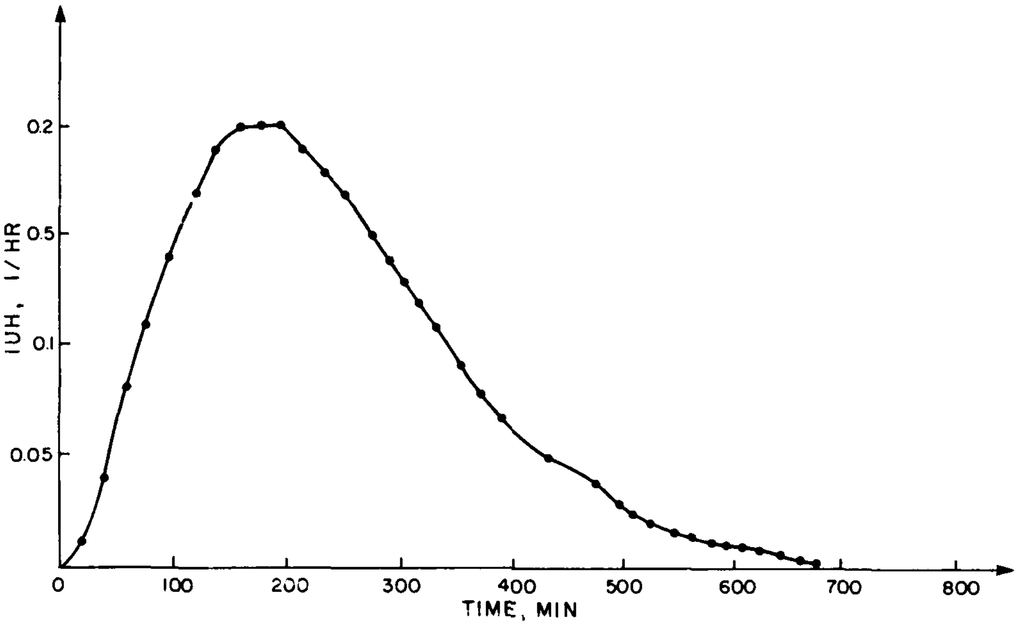

Figure 20. The instantaneous unit hydrograph of watershed G, Riesel, TX

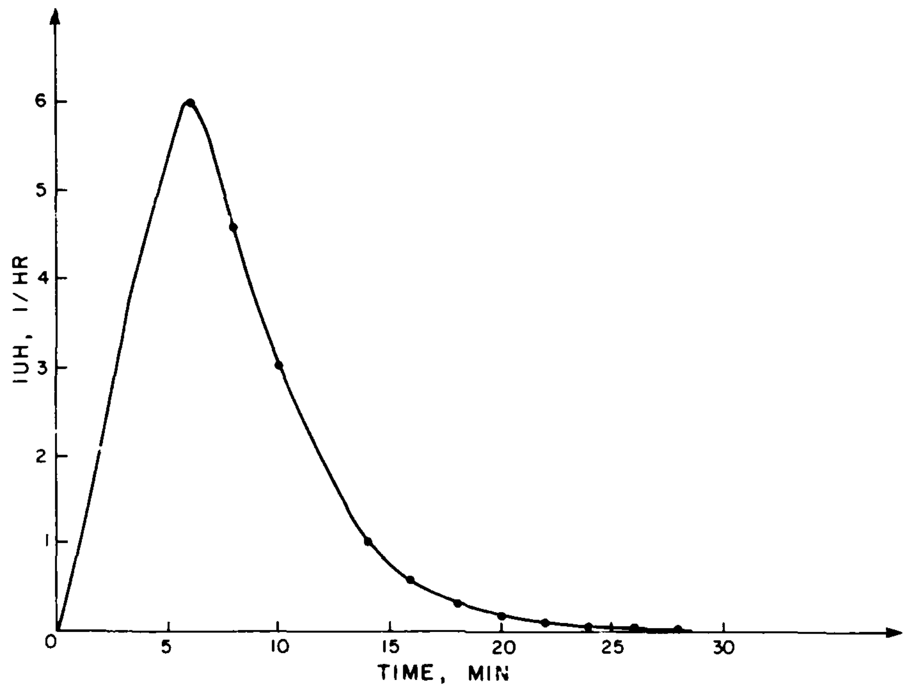

Figure 21. The instantaneous unit hydrograph of watershed Y, Riesel, TX

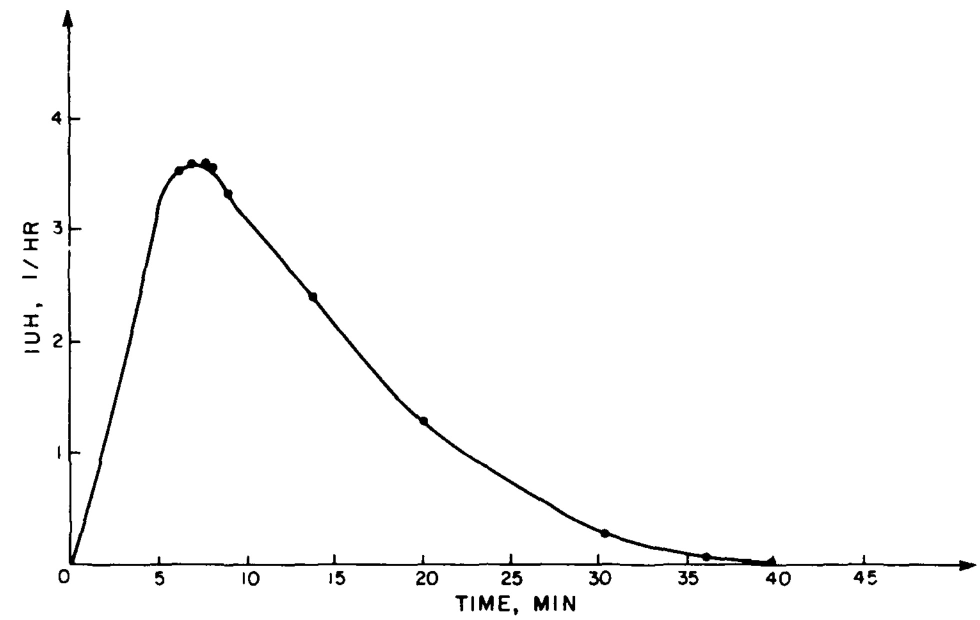

Figure 22. The instantaneous unit hydrograph of watershed 2-H, Hastings, NE

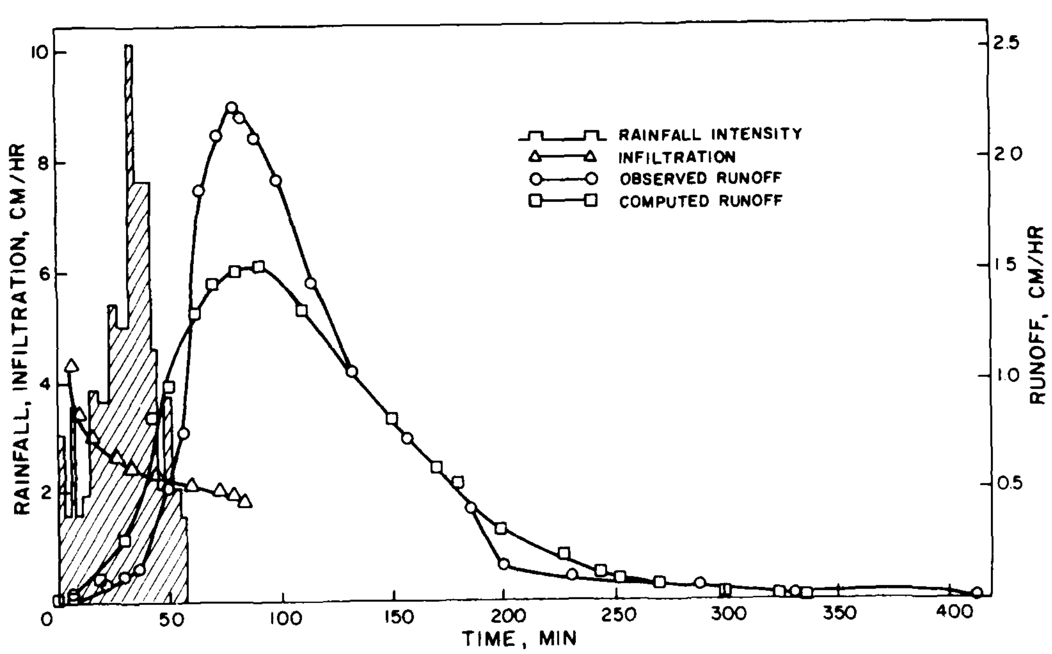

Figure 23. Comparison of observed and predicted runoff hydrographs for the rainfall-runoff event of 10 July 1941 on watershed C, Riesel, TX

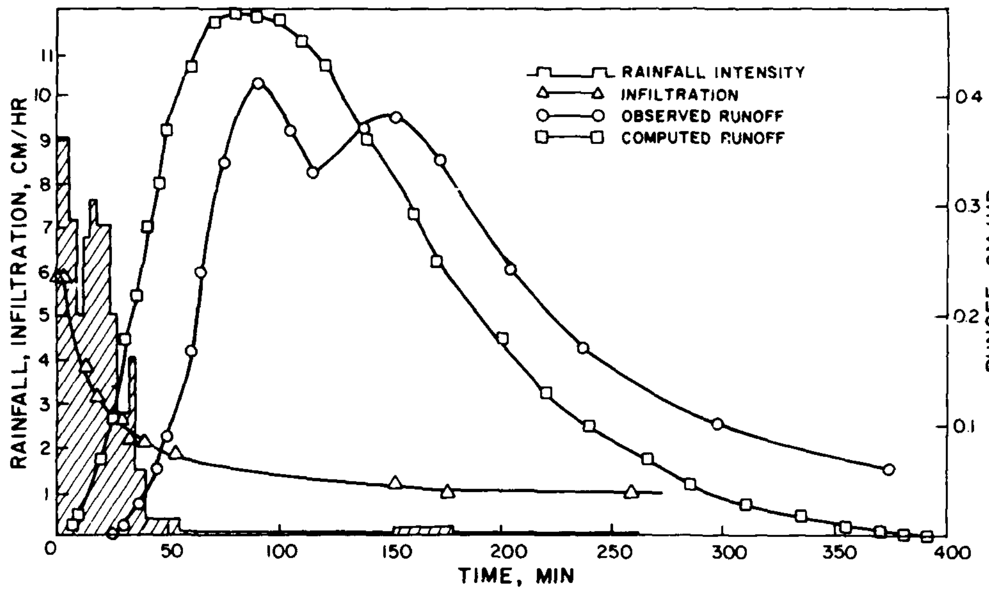

Figure 24. Comparison of observed and predicted runoff hydrographs for the rainfall-runoff event of 16 July 1961 on watershed D, Riesel, TX

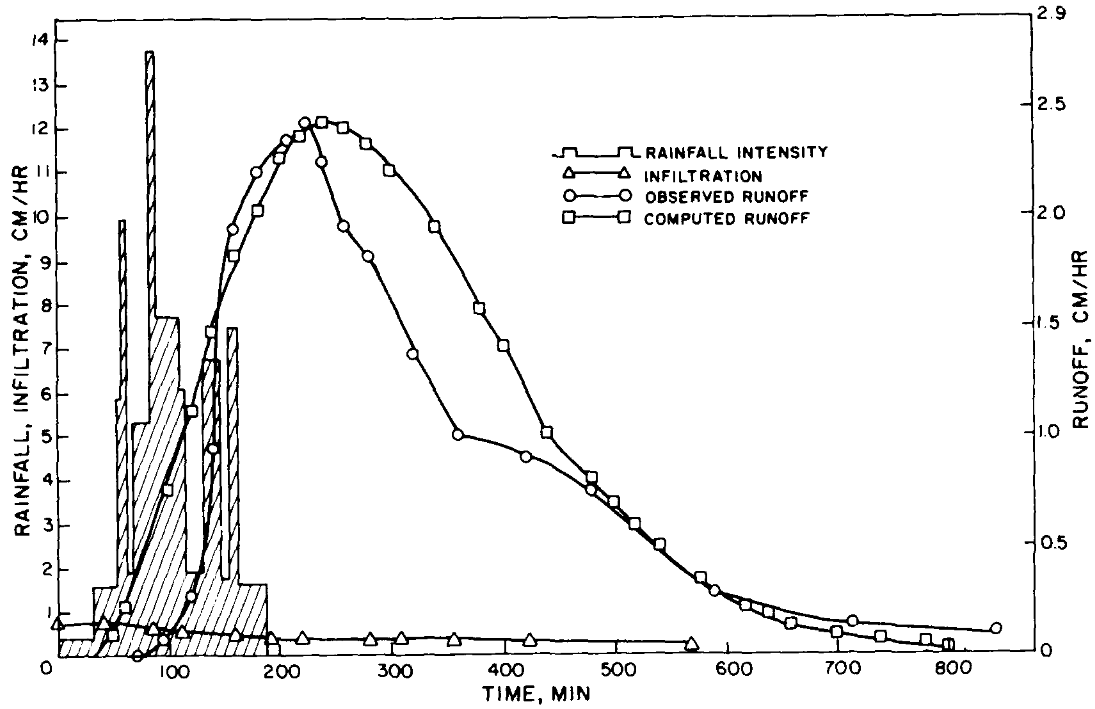

Figure 25. Comparison of observed and predicted runoff hydrographs for the rainfall-runoff event of 29 March 1965 on watershed G, Riesel, TX

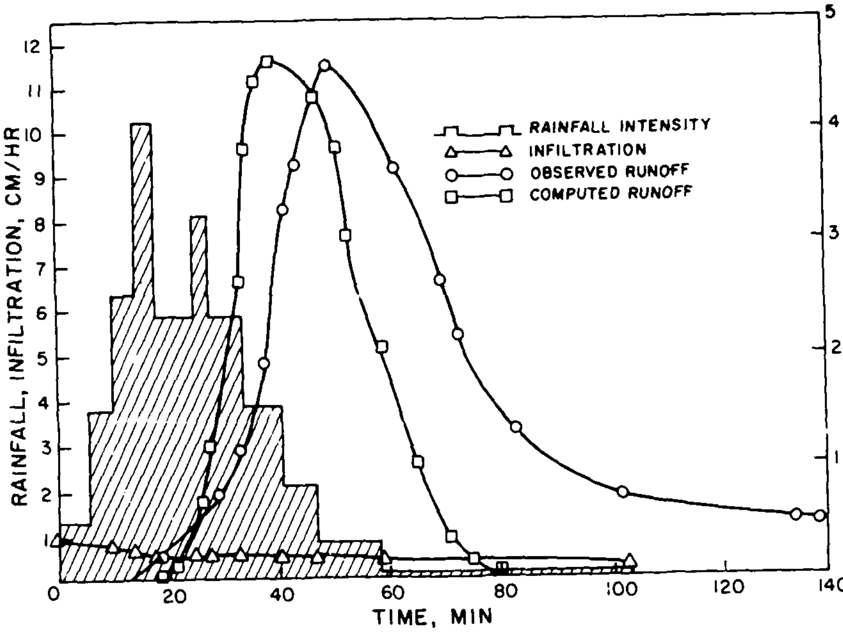

Figure 26. Comparison of observed and predicted runoff hydrographs for the rainfall-runoff event of 24 April 1957 on watershed Y, Riesel, TX

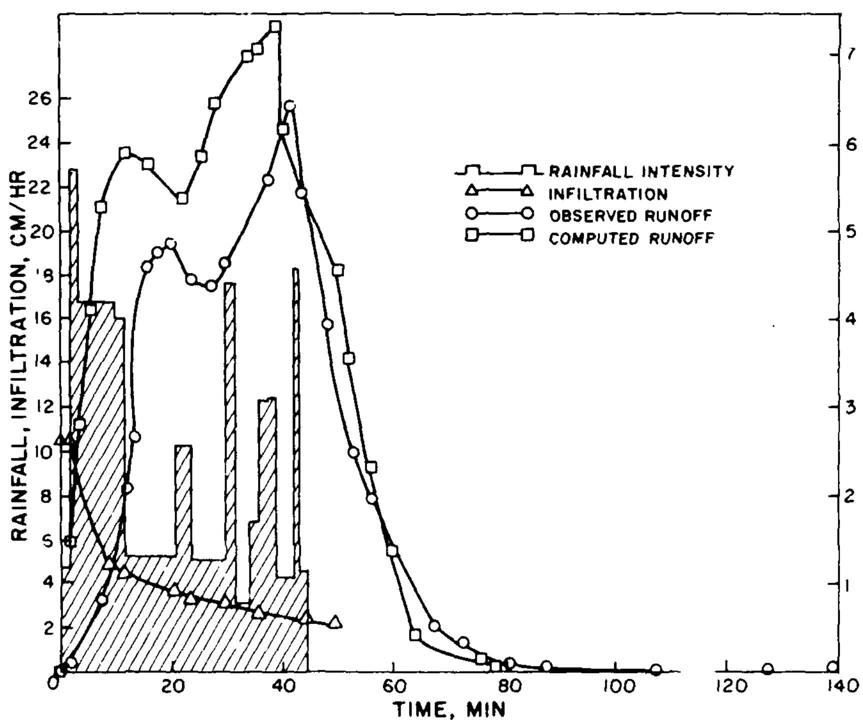

Figure 27. Comparison of observed and predicted runoff hydrographs for the rainfall-runoff event of 3 July 1959 on watershed 2-H, Hastings, NE

APPENDIX A: AN ILLUSTRATIVE EXAMPLE

Watershed 2-H, located near Hastings, NE, illustrates the highlights of the quasi-conceptual model. This watershed has been discussed previously in the main text. The steps involved in using this model are given below.

1. Compute the watershed area. Watershed 2-H has an area of $A_W = 0.0137 \text{ km}^2$.

2. Order the channel links according to the Strahler ordering scheme as shown in Figure 16.* Draw the subwatershed boundaries for each channel link. Watershed 2-H is a second-order basin. Its drainage basin properties are given in Table 5.

3. Measure the length and area of each link and overland region. For watershed 2-H, these are shown in Table 5.

4. Compute the average values of length and area for channels and overland regions respectively for each order. For watershed 2-H,

$\bar{L}_1 = 0.0184 \text{ km}$

$\bar{L}_2 = 0.062 \text{ km}$

$\bar{A}_1 = 0.00340 \text{ km}^2$

$\bar{A}_2 = 0.0070 \text{ km}^2$

5. Determine the path space and the paths for the watershed. In the present case, the number of paths is $2^{(2-1)} = 2$. Let the paths be denoted by s_1 and s_2 . The path space then is $S \equiv \{s_1, s_2\}$. The individual paths are defined as

s_1: $r_1 \rightarrow c_1 \rightarrow c_2$

s_2: $r_2 \rightarrow c_2$

6. Compute for each path s_1 and s_2 the ratio A_{ri}, $i = 1, 2$. For the watershed 2-H,

$$A_{r1} = \frac{0.0068}{0.0137} = 0.496$$

$$A_{r2} = \frac{0.007}{0.0137} = 0.511$$

7. Compute the quantity $P_{ci,cj}$. In the present case,

$$P_{c1,c2} = \frac{2}{2} = 1$$

---

* See figures and tables in the main text.

$$P_{c2,c3} = \frac{1}{1} = 1$$

c_3 represents the trapping state.

8. Compute the path probabilities $p(S)$. These will be:

$$p(s_1) = A_{r1}\, P_{r1,c1}\, P_{c1,c2} = 0.496 \times 1.0 \times 1.0 = 0.496$$

$$p(s_2) = A_{r_2}\, P_{r_2,c_2} = 0.511 \times 1.0 = 0.511$$

9. Compute the basin lag. If b in Equation 17* is assumed to be 0.875 and the exponent is 0.38, then

$$K_B = 0.875(0.0137)^{0.38} = 0.171 \text{ hr}$$

10. Compute the mean holding time of each overland flow region K_{ri} and each channel order by using Equations 11-13 in conjunction with Equation 16. For the watershed 2-H,

$$K_B = p(s_1)\left(\frac{1}{K_{r1}} + \frac{1}{K_{c1}} + \frac{1}{K_{c2}}\right) + p(s_2)\left(\frac{1}{K_{r2}} + \frac{1}{K_{c2}}\right)$$

$$\frac{1}{K_{r1}} = a\left(\frac{A_{r1}A_w}{2N_1\bar{L}_1}\right)^{1/3} = a\left(\frac{0.496 \times 0.0137}{2 \times 2 \times 0.0184}\right)^{1/3}$$

$$= a \times 0.4520$$

$$\frac{1}{K_{r2}} = a\left(\frac{0.511 \times 0.0137}{2 \times 1 \times 0.062}\right)^{1/3}$$

$$= a \times 0.3836$$

$$\frac{1}{K_{c1}} = a(0.0184)^{1/3} = a \times 0.2640$$

$$\frac{1}{K_{c2}} = a(0.062)^{1/3} = a \times 0.3958$$

---

* See equations in the main text.

Therefore,

$$0.171 = a[(0.4520 + 0.2640 + 0.3958)(0.496) + (0.3836 + 0.3958)(0.511)]$$
$$= a(0.5514 + 0.3983)$$
$$= a(0.950)$$

This yields

$$a = \frac{0.171}{0.950} = 0.180$$

Using this value of a, then

$$\frac{1}{K_{r1}} = 0.08136 \quad ; \quad K_{r1} = 12.291$$

$$\frac{1}{K_{r2}} = 0.06900 \quad ; \quad K_{r2} = 14.483$$

$$\frac{1}{K_{c1}} = 0.04752 \quad ; \quad K_{c1} = 21.044$$

$$\frac{1}{K_{c2}} = 0.07124 \quad ; \quad K_{c2} = 14.036$$

11. For each path, arrange values of the inverse of the mean holding time in a vector according to the elements involved in the path. For the watershed 2-H,

path s_1: $< r_1, c_1, c_2 > \rightarrow < K_{r1}, K_{c1}, K_{c2} > \rightarrow$

$- 12.291, 21.044, 14.036 >$

path s_2: $< r_2, c_2 > \rightarrow < K_{r2}, K_{c2} > \rightarrow <14.483, 14.306 >$

The path probability vector is

$p(s)$: $< s_1, s_2 > \rightarrow < 0.496, 0.511 >$

12. Compute the values of C_{ij} for each path s_1 and s_2 using Equation 9. In the present case, the following is obtained for the path s_1 :

$$C_{13} = \frac{K_{r1} K_{c1}}{(K_{c1} - K_{r1})(K_{c2} - K_{r1})} = \frac{12.291 \times 21.044}{(21.044 - 12.291)(14.036 - 12.291)}$$
$$= 16.934$$

$$C_{23} = \frac{K_{r1} K_{c1}}{(K_{r1} - K_{c1})(K_{c2} - K_{c1})} = \frac{12.291 \times 21.044}{(12.291 - 21.044)(14.036 - 21.044)}$$
$$= 4.2166$$

$$C_{33} = \frac{K_{r1} K_{c1}}{(K_{r1} - K_{c2})(K_{c1} - K_{c2})} = \frac{12.291 \times 21.044}{(12.291 - 14.036)(21.044 - 14.036)}$$
$$= -21.151$$

and for path s_2 ,

$$C_{12} = \frac{K_{r2}}{(K_{c2} - K_{r2})} = \frac{14.483}{(14.036 - 14.483)} = -32.400$$

$$C_{22} = \frac{K_{r2}}{(K_{r2} - K_{c2})} = \frac{14.483}{(14.483 - 14.036)} = 32.400$$

13. Compute the IUH using Equation 10. For the watershed 2-H, the following is obtained,

$$h(t) = [C_{13} \exp(-K_{r1}t) + C_{23} \exp(-K_{c1}t) + C_{33} \exp(-K_{c2}t)]$$
$$p(s_1) + [C_{12} \exp(-K_{r2}t) + C_{22} \exp(-K_{c2}t)]\ p(s_2)$$
$$= [16.934 \exp(-12.291t) + 4.2166 \exp(-21.044t)$$
$$- 21.151 \exp(-14.036t)]\ 0.496 + [-32.400 \exp(-14.483t)$$
$$+ 32.400 \exp(-14.036t)]\ 0.511$$

For different values of time, the instantaneous unit hydrograph (IUH) can be computed as shown in Table A1.

Table A1

IUH for Watershed 2-H Located near Hastings, NE

Time min	Time hr	h(t) 1/hr
0	0.000	0.0000
2	0.033	0.1954
4	0.067	0.2909
6	0.100	0.3124
8	0.133	0.2906
10	0.167	0.2489
12	0.200	0.2021
14	0.233	0.1579
16	0.267	0.1200
18	0.300	0.0893
20	0.333	0.0653
22	0.367	0.0471
24	0.400	0.0336
26	0.433	0.0238
28	0.467	0.0167
30	0.500	0.0116
32	0.533	0.0081
34	0.567	0.0056
36	0.600	0.0038
38	0.633	0.0026
40	0.667	0.0018
42	0.700	0.0012
44	0.733	0.0008
46	0.767	0.0006
48	0.800	0.0004
50	0.833	0.0003

APPENDIX B: USER INSTRUCTIONS

1. The quasi-conceptual model based on drainage basin morphometry for direct runoff hydrograph synthesis (GMHS) requires data only on storm rainfall, soil infiltration characteristics, and the drainage network characteristics of a basin. Thus, the model can potentially be applied to synthesize direct runoff hydrographs on ungaged basins. To obtain data on drainage network properties, it is sufficient to have a topographic map, preferably with a scale of 1:24,000. Topographic maps for most of the basins in the United States are available from the US Geological Survey. Data on rainfall and soil infiltration characteristics used in this study were obtained from the US Department of Agriculture publication entitled "Hydrologic Data on Experimental Agricultural Watersheds in the United States."

2. The GMHS contains a number of subroutines, the use of which depends upon whether parameter optimization is or is not required. The arrangement or sequencing of the subroutines is shown in Figure 2.* A computer program was developed and is available in the form of a Fortran IV deck. The major functions of the program are shown in Figure 3.

3. As for all programs, the preparation of input data is critical. Some common requirements are as follows. All integer numbers must be right justified, that is, placed as far to the right in the available field as possible. Decimal points are necessary unless integer numbers are used. When a decimal point is used, it must occupy a location in the field just as an integer would. For example, the number 19.8934 would require at least seven spaces in the field. If more than one card of the same format is included in the deck, the location of the decimal points should be kept the same from one card to another to facilitate key-punching of the cards. The following discussion provides information on input variables, data, and formats for specific subroutines in the program.

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* See main text for figures and tables.

4. This constitutes the main program. It provides general information about the model, for example its purpose, and calls for execution of the model. Its input is given as follows:

- a. Specify the purpose of the computer program such as, "The purpose of this program is to synthesize a runoff hydrograph using drainage network properties." This statement is denoted by PURP and appears on cards 1 and 2 at the start of the program. The user may enter any alphanumeric information on columns 1-80 of two consecutive cards. This is specified as (PURP(I),I=1,40) using an A-format as FORMAT(20A4). This information will be printed at the beginning of the computer output to indicate the purpose of the program.

- b. Specify the time interval of computation and the number of basins under study. These are denoted respectively by DT and NW and are given on card 3. The format for reading them is FORMAT(F10.4,I5).

- c. Specify the number of rainfall-runoff events for which the program is to be used. This is denoted by NOBS and specified on card 4. The format for reading it is FORMAT(I5).

- d. Specify the parameter A of the Philip two-term model. This is denoted by AA and specified on columns 1-10 of card 5. This parameter is assumed constant for a given basin but may vary from one basin to another. On the same card are specified EX and NXM, which denote the exponent of the lag-area relationship and the number of time intervals of computation. These are entered into columns 11-20 and 21-25, respectively. The format for reading all three of them is FORMAT(2F10.4,I5).

- e. A control designated as KOPT is given on card 6. An integer number, either 0 or 1, is specified and determines whether optimization of model parameters is or is not required. When KOPT is 0, optimization is not needed. When it is 1, optimization is needed. KOPT is entered into columns 1-5 and read by the format FORMAT(I5). From this point on, the card order is dependent upon whether or not optimization is performed.

- f. If optimization of model parameters is required, then specify the number of rainfall-runoff events, designated by MOBS, to be used in optimization. The format for reading it is FORMAT(I5).

- g. If optimization of model parameters is not required, then model parameters must be specified. Provide the lag parameter that is denoted by PAR. The format for it is FORMAT(F10.4).

- h. Read the number of rainfall-runoff events for prediction. This is denoted by NOBS. The format for reading it is FORMAT(I5).

Subroutine EXOP

5. The purpose of this subroutine is to set the stage if optimization of model parameters is needed. The input for this subroutine is given as follows:

a. Specify the number of parameters for optimization denoted by N, number of stage searches desired by optimization algorithm denoted by MST, control value for printing of results of optimization algorithm denoted by IPT, convergence tolerance based on change of objective function denoted by EPS, and weighting factor denoted by WF to be used in defining the objective function. When IPT = 0 , only the final parameter values are printed. When IPT = 1 , parameter values at each stage search are printed. When IPT = 2 , parameter values at each cycle search are printed. These are read as READ(5,.)N,MST, IPT,EPS,WF using the format FORMAT(3I5,F15.6,F10.4).

b. Specify initial guesses of the parameters denoted by PAR(I), I=1,2,...,n, where n is the number of parameters to be optimized. These are necessary to start the optimization algorithm. These are read as READ(5,.)(PAR(I),I=1,N) with the format FORMAT(8F10.4).

c. Specify lower limits of the parameter values denoted by PL(I), I=1,2,...,n. These are ready as READ(5,.)(PL(I), I=1,N) with the format FORMAT(8F10.4).

d. Specify upper limits of the parameter values denoted by PU(I), I=1,2,...,n. These are read as READ(5,.)(PU(I),I=1,N) with the format FORMAT(8F10.4).

6. The lower and upper limits define the range from which optimal parameter values must be derived.

Subroutine OBJECT

7. This subroutine computes the objective function for optimization. No input is read in this subroutine.

Subroutine PRECIP

8. This subroutine reads rainfall-runoff data for a given watershed. Employing the information furnished by the subroutines NEWTON and INFIL, it computes the effective rainfall and arranges it in a proper manner. The input to this subroutine is given as follows:

a. Specify the number of rainfall readings in a given event. This is denoted by NNQ. This is read by READ(5,.)NNQ with the format FORMAT(I5).

b. Specify the date and the watershed on which the rainfall event occurred. This is denoted by INF. The read statement for this is READ(5,.)(INF(I),I=1,20) with the format FORMAT(20A4).

c. Specify the volumes of rainfall and direct runoff. These are denoted respectively by RVOL and QVOL. The read statement for this is READ(5,.)RVOL,QVOL with the format FORMAT(2F10.4).

d. Specify the rainfall hyetograph where time is given in hours and minutes and intensity in centimetres per hour. Depending upon the number of readings, this may be specified on several cards. The readings in hours, minutes, and intensity are denoted by IT1, IT2, and QI, respectively. The read statement for this is READ(5,.)(IT1(I),IT2(I),QI(I),I=1,NNQ) with the format FORMAT(4(2I5,F10.4)).

e. Specify the number of runoff readings. This is denoted by NQQ. The read statement for this is READ(5,.)NQQ with the format FORMAT(I5).

f. Specify the date and basin on which the runoff event occurred. This is denoted by INFQ(I). The read statement for this is READ(5,.)(INFQ(I),I=1,20) with the format FORMAT(20A4).

g. Specify the runoff hydrograph where time is given in hours and minutes and discharge in centimetres per hour. These are respectively denoted by JTQ1, JTQ2, and QOB. Depending upon the value of NQQ, these may occupy several cards. The read statement here is READ(5,.)(JTQ1(I),JTQ2(I),QOB(I),I=1,NQQ) with the format FORMAT(4(2I5,F10.4)).

Subroutine NEWTON

9. The purpose of this subroutine is to determine the Philip infiltration parameter, sorptivity S. No input data are specified in this subroutine.

Subroutine BROSEN

10. This subroutine optimizes the parameter values for a given set of rainfall-runoff events. No input is read in this subroutine.

Subroutine INFIL

11. This subroutine computes infiltration using the Philip infiltration model. No input data are specified in this subroutine.

Subroutine XDATA

12. The purpose of this subroutine is to arrange effective rainfall data at equal time intervals. No input data are required in this subroutine.

Subroutine BASIN

13. This subroutine specifies and computes pertinent geomorphic parameters. The input in this subroutine is given as follows:

- *a*. Specify the purpose of this subroutine. This is denoted by PURP and occupies two cards. The read statement is READ(5,.)(PURP(I),I=1,40) with the format FORMAT(20A4).
- *b*. Specify general information about the watershed, its location, its type, etc. This is denoted by INF and will occupy one card. The read statement is READ(5,.)(INF(I),I=1,20) with FORMAT(20A4).
- *c*. Specify the area and order of the watershed, respectively denoted by A and W. These are given on one card. The read statement is READ(5,.)A,W with FORMAT(F10.4,I5).
- *d*. Each channel element within a watershed is identified by a label indicating the channel order and sequence number of the channel element. For example, 1.3 denotes the third channel element of the first-order channel for watershed G as shown in Figure 13. This identification of channel elements is convenient but not essential. Obtain the channel order having the highest number of channel elements. Specify this number of elements by MAX and its order of the channel by OCM on the same card. The read statement is READ(5,.)MAX,OCM with the format FORMAT(2I5).
- *e*. Specify the channel order and the associated number of elements, denoted respectively by OC and NC. Depending upon the value of W, these may occupy several cards. The read statement is READ(5,.)(OC(I),NC(I),I=1,W) with FORMAT(16I5).
- *f*. Specify the number of paths available in the watershed, denoted by MS. The read statement is READ(5,.)MS with FORMAT(I5).
- *g*. Specify the path and the number of mergers of channels occurring in this path. These are denoted by PAT and MC. The read statement is READ(5,.)PAT(I),MC with FORMAT(16I5).

h. Specify for each path the number of channels of order i merging into channels of order j according to the path structure. This is done by specifying CI, CJ, and ICJ where CI denotes the number of channels of order I that will merge into a channel of order J higher than I, and ICJ number of channels of order I merging into channels of order J. Depending upon the number of possible paths, this may occupy several cards. The read statement for this is READ(5,.)(CI(J),CJ(J),ICJ(I,J),J=1,MC) with FORMAT(16I5).

i. On a card specify the channel order, denoted by OC. The read statement is READ(5,.)OC(I) with FORMAT(I5).

j. Specify the length of each element in a channel of each order. This is given by NE and CL where NE is the channel element number and CL the element length. Depending upon the number of channel elements and the watershed order, this specification may require several cards. The read statement is READ(5,.) (NE(J),CL(I,J),J=1,NCC) with the format FORMAT(5(I5,F10.2)). NCC signifies the number of channel elements of a given order.

k. Specify channel order, denoted by OC, on a card. The read statement is READ(5,.)OC(I) with FORMAT(I5).

l. Specify channel element number (NE) and area draining directly into the channel (AC). Depending on the watershed order and the number of elements, it may take several cards to make this specification. The read statement is READ(5,.)(NE(J),AC(I,J), J=1,NCC) with FORMAT(5(I5,F10.4)).

m. Specify the path number denoted by PAT. The read statement is Read (5,.)PAT(I) with FORMAT(I5).

n. Specify the path matrix. The spatial evolution of a water particle through a geomorphic network of overland regions and channels is perhaps best accounted for by considering the overland-channel flow paths that a water particle may take from the point of its landing to its arrival at the basin outlet. The specification of these paths for a watershed can be made by following the transition rules discussed previously. To illustrate, the overland-channel flow paths for watershed G can be specified as

s_1:	r_1 —	c_1 —	c_2 —	c_3 —	c_4 —	c_5
s_2:	r_1 —	c_1 ——	——	c_3 —	c_4 —	c_5
s_3:	r_1 —	c_1 ——	——	——	c_4 —	c_5
S_4:	r_1 —	c_1 —	c_2 ——	——	c_4 —	c_5
S_5:	r_2 ——	——	c_2 —	c_3 —	c_4 —	c_5
S_6:	r_2 ——	——	c_2 ——	——	c_4 —	c_5
S_7:	r3 ——	——	——	c_3 —	c_4 —	c_5
S_8:	r_4 ——	——	——	——	c_4 —	c_5

14. Here c_5 is the trapping state. It should be noted that a water particle always originates in one of the overland regions. Furthermore, a water particle travels first to the channel element associated with that overland region and then continues its journey to the outlet through higher order channel elements. The last state represents the trapping state as exemplified by c_5 for watershed G.

15. The information on the configuration of various overland-channel flow paths is supplied to the program in the following manner. An array consisting of $r_1, r_2, \ldots, r_W; c_1, c_2, \ldots, c_W$ is considered. For example, in case of watershed G such an array can be written as

$$r_1, r_2, r_3, r_4; c_1, c_2, c_3, c_4$$

A value of 1.00 or 0.0 is inserted in place of r_i or c_i, $i = 1, 2, \ldots, W$, depending upon whether or not r_i or c_i is present in a given path. If the first overland-channel flow path for watershed G is considered, then the information pertaining to this path can be coded as follows:

1.0, 0.0, 0.0, 0.0, 1.0, 1.0, 1.0, 1.0

Likewise, the entire structure of overland-channel flow paths can be coded as

1.0, 0.0, 0.0, 0.0, 1.0, 1.0, 1.0, 1.0
1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 1.0, 1.0
1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0, 1.0
1.0, 0.0, 0.0, 0.0, 1.0, 1.0, 0.0, 1.0
0.0, 1.0, 0.0, 0.0, 0.0, 1.0, 1.0, 1.0
0.0, 1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 1.0
0.0, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0, 1.0
0.0, 0.0, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0

This coded information on overland-channel flow paths becomes input to the program and specified by I denoting the path number and PATH denoting an array corresponding to overland regions and channels appearing in the path. This read statement is READ(5,.)(PATH(I,J),J=1,WW) with FORMAT(15F5.1).

Subroutine LAG

16. This subroutine computes the lag time using a lag-area relationship. No input is read in this subroutine.

Subroutine HOLD

17. This subroutine computes holding times for the paths available in the watershed. No input is read in this subroutine.

Subroutine IUH

18. This subroutine computes the instantaneous unit hydrograph (IUH) using the geomorphologic formulation. No input is read in this subroutine.

Subroutine CONVOL

19. This subroutine performs convolution of the rainfall excess with the IUH to determine the direct runoff hydrograph. No input is read in this subroutine.

```
RELEASE 2.0                    MAIN                  DATE = 83132            23/13/29
  C                              ********************************
  C                              ***    MAIN PROGRAM  GMHS     ***
  C                              ********************************
  C       ********************************************************************
  C       ***    THIS PROGRAM SYNTHESIZES THE SURFACE RUNOFF HYDROGRAPH USING  ***
  C       ***    THE MODEL  GMHS .                                              ***
  C       ********************************************************************
          DIMENSION PUPP(40),OBY(20),OBYT(20),NX(20),PR(10)
          COMMON/OBJ/OBY,OBYT,NX
          COMMON/POB/A,MS,W,WW
          COMMON/POM/DT,EX,WF,KOPT
          COMMON/ROSE/PR
          REAL KB
          INTEGER W,WW
  C       ******************************************************
  C       ***    FAC CONVERTS INCHES TO CENTIMETERS           ***
  C       ***    CF CONVERTS METERS TO FEET                   ***
  C       ***    PUPP(I) SPECIFIES THE PURPOSE OF THE PROGRAM ***
  C       ******************************************************
          CF= 3.2808
          FAC= 2.54
          READ(5,5) (PUPP(I),I=1,40)
        5 FORMAT(20A4)
          WRITE(6,10) (PUPP(I),I=1,40)
       10 FORMAT(5X,20A4)
  C       *******************************************************
  C       ***    NW SPECIFIES THE NUMBER OF BASINS UNDER STUDY    ***
  C       ***    DT SPECIFIES THE TIME INTERVAL OF COMPUTATION    ***
  C       *******************************************************
          READ(5,35) DT,NW
       35 FORMAT(F10.4,I5)
          WRITE(6,45) DT,NW
       45 FORMAT(5X,'TIME INTERVAL FOR COMPUTATION IN HOURS IS =',F10.4/5X,
         1'THE NUMBER OF WATERSHEDS FOR STUDY IS=',I5/)
          DO 50 J=1,NW
  C       ****************************************************************
  C       ***    NOBS IS THE NUMBER OF RAINFALL-RUNOFF EVENTS FOR A BASIN  ***
  C       ****************************************************************
          READ(5,25) NOBS
       25 FORMAT(I5)
          WRITE(6,100)NOBS
      100 FORMAT(5X,'NUMBER OF RAINFALL-RUNOFF EVENTS AVAILABLE ON THE
         1WATERSHED =',I5/)
  C       ************************************************************
  C       ***    AA IS THE PHILIP INFILTRATI6N PARAMETER APPROXIMATELY    ***
  C       ***    EQUAL TO THE SATURATED HYDRAULIC CONDUCTIVITY            ***
  C       ***    EX=EXPONENT IN THE LAG-AREA RELATION                     ***
  C       ***    NXM IS THE NUMBER OF COMPUTATION TIME INTERVALS          ***
  C       ************************************************************
          READ(5,80)AA,EX,NXM
       80 FORMAT(2F10.4,I5)
          WRITE(6,110) EX
      110 FORMAT(5X,'EXPONENT IN THE LAG-AREA RELATION=',F10.4/)
          AA=AA*FAC
          WRITE(6,105)NXM
      105 FORMAT(5X,'NUMBER OF COMPUTATION STEPS IS =',I5/)
          WRITE(6,85)AA
       85 FORMAT(5X,'PHILIP PARAMETER A(CM/HR)=',F10.4/)
```

```
      READ(5,15)KOPT
   15 FORMAT(I5)
      CALL BASIN(A,MS,W,WW)
      IF(KOPT.EQ.0) GO TO 20
      WRITE(6,65)KOPT
   65 FORMAT(5X,'OPTIMIZATION OF PARAMETERS IS REQUIRED AND OPTIMIZATION
     1CODE IS',I5)
C     ************************************************************************
C     ***    DEFINE THE NUMBER OF RAINFALL-RUNOFF EVENTS TO BE USED IN     ***
C     ***    OPTIMIZATION                                                  ***
C     ***    MOBS=NUMBER OF RAINFALL-RUNOFF EVENTS USED IN PARAMETER       ***
C     ***    OPTIMIZATION                                                  ***
C     ************************************************************************
      READ(5,25) MOBS
      WRITE(6,30) MOBS
   30 FORMAT(5X,'NUMBER OF RAINFALL-RUNOFF EVENTS FOR OPTIMIZATION IS'
     1,2X,I5/)
      CALL EXOP(MOBS,NXM,AA,A)
      NOBS=NOBS-MOBS
      GO TO 70
   20 WRITE(6,75)KOPT
   75 FORMAT(5X,'PARAMETERS ARE KNOWN AND NO OPTIMIZATION IS NECESSARY'/
     15X,'NO OPTIMIZATION CODE IS',I3/)
C     *********************************************************************
C     ***    PAR IS THE PROPORTIONALITY FACTOR AND EX THE EXPONENT IN   ***
C     ***    LAG-AREA RELATION WHERE AREA IS IN SQUARE KILOMETERS AND   ***
C     ***    KOPT IS ALSO USED AS A CONTROL FOR PRINTING OUTPUT IN A    ***
C     ***    LAG IN HOURS                                               ***
C     ***    GIVEN SUBROUTINE                                           ***
C     *********************************************************************
      READ(5,55) PAR
   55 FORMAT(F10.4)
      WRITE(6,60)PAR,EX
   60 FORMAT(5X,'PARAMETER ALPHA IN LAG(HRS) AREA(KM**2) RELATION IS=',
     1F10.4/5X,' EXPONENT IN LAG AREA RELATION IS=',F10.4/)
      READ(5,25)NOBS
   70 CONTINUE
      KOPT=0
      WRITE(6,96)NOBS
   96 FORMAT(5X,'NUMBER OF RAINFALL RUNOFF EVENTS FOR PREDICTION IS',
     1I5/)
      PAR=PR(1)
      CALL LAG(A,PAR,EX,KB)
      CALL HOLD(MS,W,A,WW,KB,KOPT)
      CALL IUH(MS,WW,DT,KOPT)
      DO 40 I=1,NOBS
      CALL PRECIP(NNQ,DT,AA,OBQ,OBQT,A)
      CALL XDATA(NNQ,NXM,DT)
      CALL CONVOL(DT,NXM,QP,QPT,KOPT,A)
      QERR=(OBQ-QP)/OBQ
      QTERR=(OBQT-QPT)/OBQT
      WRITE(6,115) OBQ,QP,QERR
  115 FORMAT(5X,'OBS.PEAK DISCHARGE(CM/HR)=',F10.4,2X,'COMP. PEAK
     1DISCHARGE=',F10.4,2X,'RELATIVE ERROR=',F10.4/)
      WRITE(6,120) OBQT,QPT,QTERR
  120 FORMAT(5X,'OBS.PEAK TIME (MIN)=',F10.3,2X,'COMP. PEAK TIME (MIN)=
     1',F10.3,2X,'RELATIVE ERROR =',F10.4/)
   40 CONTINUE
```

```
   50 CONTINUE
      STOP
      END
```

```
      SUBROUTINE EXOP(MOBS,NXM,AA,A)
C     ******************************************************************
C     ***  THE PURPOSE OF THIS SUBROUTINE IS TO PROVIDE PERTINENT    ***
C     ***  INFORMATION REQUIRED BY THE OPTIMIZATION ALGORITHM.       ***
C     ******************************************************************
      DIMENSION TI(100),QI(100),X(2000),P(10,1000),PAR(10),PL(10),PU(10)
     1,NX(20),OBY(20),OBYT(20)
      COMMON/VS/TI,QI,P
      COMMON/POM/DT,EX,WF,KOPT
      COMMON/OBJ/OBY,OBYT,NX
      COMMON/PARA/PAR,PL,PU
      COMMON/VSX/X
      INTEGER W,WW
      READ(5,5)N,MST,IPT,EPS,WF
    5 FORMAT(3I5,F15.6,F10.4)
C     *********************************************************************
C     ***  N=NUMBER OF PARAMETERS                                      ***
C     ***  MST=NUMBER OF STAGE SEARCHES DESIRED                        ***
C     ***  IPT=0----ONLY THE FINAL PARAMETER VALUES PRINTED            ***
C     ***  IPT=1----INTERMEDIATE VALUES OF EACH STAGE SEARCH PRINTED   ***
C     ***  IPT=2----INTERMEDIATE VALUES OF EACH CYCLE SEARCH PRINTED   ***
C     ***  EPS=CONVERGENCE TOLERANCE BASED ON THE CHANGE OF THE        ***
C     ***  OBJECTIVE FUNCTION                                          ***
C     ***  WF= WEIGHTING FACTOR TO BE USED IN DEFINING OBJECTIVE       ***
C     ***  FUNCTION                                                    ***
C     *********************************************************************
      WRITE(6,10)N,EPS
   10 FORMAT(5X,'NUMBER OF PARAMETERS =',I5,3X,'CONVERGENCE TOLERANCE
     1LIMIT=',E15.7/)
      WRITE(6,15)MST,IPT
   15 FORMAT(5X,'NUMBER OF STAGE SEARCHES SPECIFIED=',I5,5X,'CODE FOR
     1PRINTING PARAMETER VALUES=',I5/)
      WRITE(6,45)WF
   45 FORMAT(5X,'WEIGHTING FACTOR USED IN DEFINITION OF OBJECTIVE
     1FUNCTION=',F10.4/)
C     ***************************************************
C     ***  PAR(I)=INITIAL GUESS OF I-TH PARAMETER   ***
C     ***  PL(I)=LOWER BOUND OF I-TH PARAMETER      ***
C     ***  PU(I)=UPPER BOUND OF I-TH PARAMETER      ***
C     ***************************************************
      READ(5,20)(PAR(I),I=1,N)
   20 FORMAT(8F10.4)
      READ(5,20) (PL(I),I=1,N)
      READ(5,20) (PU(I),I=1,N)
      WRITE(6,25) (PAR(I),I=1,N)
   25 FORMAT(5X,' INITIAL PARAMETER GUESSES ARE',8F10.4/)
      WRITE(6,30) (PL(I),I=1,N)
   30 FORMAT(5X,' LOWER LIMITS OF PARAMETER VALUES ARE',8F10.4/)
      WRITE(6,35) (PU(I),I=1,N)
   35 FORMAT(5X,'UPPER LIMITS OF PARAMETER VALUES ARE', 8F10.4/)
      DO 40 I=1,MOBS
      CALL PRECIP(NNQ,DT,AA,OBQ,OBQT,A)
      OBY(I)=OBQ
      OBYT(I)=OBQT
      CALL XDATA(NNQ,NXM,DT)
      NX(I)=NXM
      DO 37 J=1,NXM
   37 P(I,J)=X(J)
```

```
   40 CONTINUE
      CALL BROSEN(N,MST,IPT,EPS,MOBS)
      RETURN
      END
```

```
      SUBROUTINE OBJECT(VALUE,MOBS,N)
C     ******************************************************************
C     ***    THIS PROGRAM SPECIFIES THE OBJECTIVE FUNCTION TO BE USED IN     ***
C     ***    OPTIMIZATION OF PARAMETERS                                      ***
C     ***    THE OBJECTIVE FUNCTION IS DEFINED HERE AS THE SUM OF SQUARES    ***
C     ***    OF DEVIATIONS BETWEEN OBSERVED AND COMPARED PEAKS AND/OR         ***
C     ***    THEIR TIMES OF OCCURENCE                                        ***
C     ******************************************************************
      DIMENSION  PR(10),NX(20),P(10,1000),PREDY(20),X(2000),OBY(20)
     1,OBYT(20),PREDT(20),TI(100),QI(100)
      COMMON/ROSE/PR
      COMMON/OBJ/OBY,OBYT,NX
      COMMON/PCB/A,MS,W,WW
      COMMON/POM/DT,EX,WF,KOPT
      COMMON/VS/TI,QI,P
      COMMON/VSX/X
      REAL KP,KB
      INTEGER W,WW
      WRITE(6,5) (PR(I),I=1,N)
    5 FORMAT(5X,'INITIAL PARAMETER GUESSES ARE',8F10.4/)
      KP=PR(1)
      CALL LAG(A,KP,EX,KB)
      CALL HOLD(MS,W,A,WW,KB,KOPT)
      CALL IUH(MS,WW,DT,KOPT)
      DO 15 I=1,MOBS
      NXM=NX(I)
      DO 20 J=1,NXM
   20 X(J)=P(I,J)
      CALL CONVOL(DT,NXM,QP,QPT,KOPT,A)
      PREDY(I)=QP
      PREDT(I)=QPT
   15 CONTINUE
      WRITE(6,10)
   10 FORMAT(5X,'OBSERVED PEAK',2X,'PREDICTED PEAK',2X,'ERROR=QO-QP',2X
     1,'OBS.PEAK TIME',2X,'PRED. PEAK TIME',2X,'ERROR=TPO-TPC'/)
      VALUE1=0.00
      VALUE2=0.00
      DO 25 I=1,MOBS
      DEVQ=OBY(I)-PREDY(I)
      TEMP=DEVQ*DEVQ
      VALUE1=VALUE1+TEMP
      DEVT=OBYT(I)-PREDT(I)
      TEMPT=DEVT*DEVT
      VALUE2=VALUE2+TEMPT
      WRITE(6,30)  OBY(I),PREDY(I),DEVQ,OBYT(I),PREDT(I),DEVT
   30 FORMAT(6(5X,F10.4))
   25 CONTINUE
      VALUE=WF*VALUE1+(1.0-WF)*VALUE2
      VMQ=VALUE1/FLOAT(MOBS)
      VMT=VALUE2/FLOAT(MOBS)
      WRITE(6,35)VALUE,VMQ,VMT
   35 FORMAT(5X,' OBJECTIVE FUNCTION VALUE=',E15.7/5X,' MEAN SQUARE
     1ERROR IN HYDROGRAPH PEAK=', E15.7/5X,' MEAN SQUARE ERROR IN TIME
     2TO HYDROGRAPH PEAK=', E15.7/)
      RETURN
      END
```

```
      SUBROUTINE BASIN(A,MS,W,WW)
C     ******************************************************************
C     ***   THE PURPOSE OF THIS SUBROUTINE IS TO PROVIDE PERTINENT   ***
C     ***   GEOMORPHOLOGIC INFORMATION REQUIRED BY THE GMHS MODEL    ***
C     ******************************************************************
      DIMENSION PUPP(40),INF(20),NC(20),ICJ(20,20),CL(20,50),AL(20),
     1AC(20,50),SA(20),AR(20),PC(20,20),MF(20),PS(20),PA(20),PATH(20,20)
     1,PAT(20),CI(20),CJ(20),OC(20),NE(20)
      COMMON/ONE/AR,NC,AL
      COMMON/TWO/PATH,PS
      INTEGER W,WW,CI,CJ,PAT,OCM,OC
      COEF=1.0
      CFF=1.0
C     ***********************************************************
C     ***   PUPP(I) SPECIFIES THE PURPOSE OF THIS SUBROUTINE   ***
C     ***   INF(I) GIVES NAME AND  LOCATION OF THE BASIN       ***
C     ***********************************************************
      READ(5,5) (PURP(I),I=1,40)
    5 FORMAT(20A4)
      WRITE(6,5) (PURP(I),I=1,40)
      READ(5,10) (INF(I),I=1,20)
   10 FORMAT(20A4)
      WRITE(6,15)(INF(I),I=1,20)
   15 FORMAT(5X,20A4)
C     **********************************************************************
C     ***   THE LENGTH AND AREA ARE IN KILOMETERS AND SQUARE KILOMETERS  ***
C     ***   RESPECTIVELY.IF NOT THEN CHANGE CFF AND COEF FROM 1.0 TO     ***
C     ***   APPROXIMATE VALUES                                           ***
C     ***   A DENOTES BASIN AREA. IF AREA IS NOT IN SQUARE KILOMETERS    ***
C     ***   THEN CONVERT IT TO THESE UNITS                               ***
C     **********************************************************************
      READ(5,20) A,W
   20 FORMAT(F10.4,I5)
      A=A*COEF
      WRITE(6,21) A,W
   21 FORMAT(5X,'BASIN AREA(SQ KM)=',F10.3,5X,'ORDER OF THE BASIN=',I5/)
C     **********************************************************************
C     ***   OCM GIVES THE CHANNEL ORDER WHICH HAS HIGHEST NUMBER OF THE  ***
C     ***   ELEMENTS DENOTED BY MAX                                      ***
C     **********************************************************************
      READ(5,22) MAX,OCM
   22 FORMAT(2I5)
      WRITE(6,25) MAX,OCM
   25 FORMAT(5X,'MAXIMUM NUMBER OF ELEMENTS=',I5,2X,'IN CHANNEL ORDER=',
     1I5/)
C     ****************************************************************
C     ***   NC IS NUMBER OF CHANNEL ELEMENTS AND OC CHANNEL ORDER   ***
C     ****************************************************************
      READ(5,30) (OC(I),NC(I),I=1,W)
   30 FORMAT(16I5)
      WRITE(6,35) (OC(I),NC(I),I=1,W)
   35 FORMAT(5X,'CHANNEL ORDER=',I5,5X,'NUMBER OF CHANNEL ELEMENTS=',I5)
C     *******************************************************************
C     ***   COMPUTE THE NUMBER OF POSSIBLE PATHS IN THE WATERSHEDS     ***
C     *******************************************************************
      MS=2**(W-1)
      WRITE(6,55)MS
   55 FORMAT(5X,'NUMBER OF POSSIBLE PATHS IS=',I5/)
```

```
C      ***************************************************************
C      ***   READ THE NUMBER OF AVAILABLE PATHS IN THE WATERSHEDS   ***
C      ***************************************************************
       READ(5,130) MS
   130 FORMAT(I5)
       WRITE(6,135) MS
   135 FORMAT(5X,'NUMBER OF AVAILABLE PATHS IN THIS WATERSHED IS =',I5/)
C      ***********************************************************************
C      ***   SPECIFY THE NUMBER OF CHANNELS OF ORDER I MERGING INTO CHANNE  ***
C      ***   LS OF ORDER J ACCORDING TO THE ACTUAL PATH COMPOSITION         ***
C      ***   PAT DENOTES PATH NUMBER                                        ***
C      ***   MC DENOTES NUMBER OF MERGERS                                   ***
C      ***   CI AND CJ DENOTE ORDER OF CHANNELS I MERGING INTO ORDER J      ***
C      ***   OF CHANNELS J. ICJ IS THE NUMBER OF CHANNELS MERGING           ***
C      ***   PC IS THE PROPORTION OF CHANNELS OF ORDER I MERGING INTO       ***
C      ***   CHANNELS OF ORDER J                                            ***
C      ***********************************************************************
       DO 36 I= 1,MS
       READ(5,37) PAT(I),MC
       READ(5,37) (CI(J),CJ(J),ICJ(I,J),J=1,MC)
       ME(I)=MC
    37 FORMAT(16I5)
       WRITE(6,39) PAT(I),MC
    39 FORMAT(5X,'THIS PATH IS = ',2X,I5,2X,'NUMBER OF MERGERS IS',2X,I5
      1/)
       WRITE(6,38) (CI(J),CJ(J),ICJ(I,J),J=1,MC)
C      ******************************************************************
C      ***   COMPUTE PROPORTION OF CHANNELS OF ORDER I MERGING IN TO   ***
C      ***   CHANNELES OF ORDER J ACCORDING TO PATH STRUCTURE          ***
C      ******************************************************************
       DO 95 J=1,MC
       JJ=CI(J)
       PC(I, )= FLOAT(ICJ(I,J))/FLOAT(NC(JJ))
    95 CONTINUE
       WRITE(6,100)(CI(J),CJ(J),PC(I,J),J=1,MC)
   100 FORMAT(5X,'PROPORTION OF CHANNELS OF ORDER',2X,I5,2X,'MERGING INTO
      1 CHANNELS OF ORDER',2X,I5,2X,'IS=',F10.4/)
    36 CONTINUE
    38 FORMAT(5X,'NUMBER OF CHANNELS OF ORDER',1X,I2,2X,'MERGING INTO CHA
      1NNELS OF ORDER',1X,I2,1X,'IS=',2X,I5/)
C      ***************************************
C      ***   SPECIFY THE CHANNEL LENGTHS   ***
C      ***************************************
       DO 41 I=1,W
       NCC=NC(I)
       READ(5,880) OC(I)
   880 FORMAT(I5)
C      ***********************************************************************
C      ***   NE IS THE SEQUENCE NUMBER ASSIGNED TO A CHANNEL ELEMENT OF A   ***
C      ***   GIVEN ORDER AND CL THE LENGTH OF THIS ELEMENT                  ***
C      ***   IF CL IS NOT SPECIFIED IN KILOMETERS THEN CONVERT IT TO THESE  ***
C      ***   UNITS                                                          ***
C      ***********************************************************************
       READ(5,42) (NE(J),CL(I,J),J=1,NCC)
    42 FORMAT(5(I5,F10.2))
       WRITE(6,43) OC(I)
    43 FORMAT(5X,'CHANNEL ORDER IS =',2X,I5/)
       DO 140 J=1,NCC
```

```
  149 CL(I,J)=CL(I,J)*CFF
      WRITE(6,44) (NE(J),CL(I,J),J=1,NCC)
   44 FORMAT(5X,'CHANNEL ELEMENT NUMBER=',I2,2X,
     1'ELEMENT LENGTH(KM)=',F10.3/)
   41 CONTINUE
C     ************************************************************
C     ***   COMPUTE AVERAGE LENGTH OF CHANNELS OF EACH ORDER   ***
C     ************************************************************
      DO 46 I=1,W
      SUM=0.0
      NCC=NC(I)
      DO 49 J=1,NCC
      SUM=SUM+CL(I,J)
   49 CONTINUE
C     ***********************************************************************
C     ***   AL IS THE AVERAGE LENGTH OF CHANNELS OF A GIVEN ORDER          ***
C     ***   AC IS THE DRAINAGE AREA OF A CHANNEL ELEMENT.IF THE AREA IS    ***
C     ***   NOT IN KILOMETERS THEN CONVERT IT TO THESE UNITS               ***
C     ***   SA(I) IS THE OVERLAND AREA OF ORDER I                          ***
C     ***   AR(I) IS THE RATIO OF OVERLAND AREA OF ORDER I TO BASIN AREA   ***
C     ***********************************************************************
      AL(I)=SUM/NCC
   46 CONTINUE
      WRITE(6,47) (I,AL(I),I=1,W)
   47 FORMAT(5X,'CHANNEL ORDER=',2X,I5,2X,'AVERAGE LENGTH=',F10.3/)
C     **********************************************
C     ***   SPECIFY AREA OF EACH CHANNEL ELEMENT   ***
C     **********************************************
      DO 50 I=1,W
      NCC=NC(I)
      READ(5,880) OC(I)
      READ(5,40)    (NE(J),AC(I,J),J=1,NCC)
   40 FORMAT(5(I5,F10.4))
      DO 145 J=1,NCC
  145 AC(I,J)=AC(I,J)*COEF
      WRITE(6,45)OC(I)
   45 FORMAT(5X,'CHANNEL ORDER IS =',I5/)
      WRITE(6,48) (NE(J),AC(I,J),J=1,NCC)
   48 FORMAT(5X,'CHANNEL ELEMENT NUMBER =',2X,I5,2X,
     15X,'AREA (SQ KM)=',F10.3/)
   50 CONTINUE
C     ************************************************************************
C     ***   COMPUTE SURFACE AREAS OF CHANNELS OF EACH ORDER AND THEREFORE   ***
C     ***   OF EACH PATH                                                    ***
C     ***   COMPUTE OVERLAND AREA OF EACH PATH                              ***
C     ************************************************************************
      DO 56 I=1,W
      SUM=0.0
      NCC=NC(I)
      DO 57 J=1,NCC
      SUM=SUM+AC(I,J)
   57 CONTINUE
      SA(I)=SUM
      AR(I)=SA(I)/A
   56 CONTINUE
      WRITE(6,85) (SA(I),OC(I),AR(I),I=1,W)
   85 FORMAT(5X,'AREA OF REGION(SQ KM)=',F10.2,2X,'OF ORDER=',I5,2X,'RAT
     1IO OF REGION AREA TO BASIN AREA =',F10.4/)
```

```
C     ************************************
C     ***    SPECIFY THE PATH MATRIX    ***
C     ************************************
      WW=2*W
      WRITE(6,65)
   65 FORMAT(5X,'THE PATH MATRIX IS AS FOLLOWS'/)
      DO 75 I=1,MS
C     *****************************************************************
C     ***   PATH IS THE PATH MATRIX WHOSE DIMENSIONS WOULD BE NUMBER OF ***
C     ***  PATHS X TWOFOLD BASIN ORDER                               ***
C     *****************************************************************
      READ(5,61) PAT(I)
  61  FORMAT(I5)
      WRITE(6,71) PAT(I)
  71  FORMAT(5X,'PATH=',I2/)
      READ(5,60)        (PATH(I,J),J=1,WW)
   60 FORMAT(15F5.1)
      WRITE(6,70)        (PATH(I,J),J=1,WW)
   70 FORMAT(5X,10F10.1)
   75 CONTINUE
      DO 120 I=1,MS
      DO 125 J=1,W
      IF(PATH(I,J).LE.0.0) GO TO 125
      PA(I)=AP(J)
  125 CONTINUE
  120 CONTINUE
      DO 105 I=1,MS
      TEMP=1.0
      MC=MF(I)
      DO 110 J=1,MC
      PROD=PC(I,J)*TEMP
      TEMP=PROD
  110 CONTINUE
      PS(I)=TEMP*PA(I)
      WRITE(6,115) I,PS(I)
  115 FORMAT(5X,'PATH NUMBER=',I5,5X,'PATH PROBABILITY=',F10.4/)
  105 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE LAG(A,PAR,EX,KB)
C     ************************************************************
C     ***    THIS SUBROUTINE COMPUTES THE BASIN LAG TIME    ***
C     ************************************************************
      REAL KB
C     ***********************************************
C     ***    KB IS THE BASIN LAG TIME IN HOURS    ***
C     ***********************************************
      KB=PAR*A**EX
      WRITE(6,5)A,KB
    5 FORMAT(5X,'BASIN AREA IN SQ KM =',F10.3,2X,'BASIN LAG IN HOURS =',
     1F10.2/)
      RETURN
      END
```

```
      SUBROUTINE HOLD(MS,W,A,WW,KB,KOPT)
C     ******************************************************************
C     ***     THIS SUBROUTINE COMPUTES HOLDING TIMES OF OVERLAND AND CHANNEL    ***
C     ***     FLOW REGIONS                                                      ***
C     ******************************************************************
      DIMENSION KR(20),KC(20),AL(20),NC(20),KK(20),AR(20),PATH(20,20),
     1PS(20)
      INTEGER W,WW
      REAL KR,KC,KK,KB
      COMMON/ONE/AR,NC,AL
      COMMON/TWO/PATH,PS,KK
C     ******************************************************************
C     ***     SET UP LOGIC FOR COMPUTING HOLDING TIMES FOR OVERLAND AND     ***
C     ***     CHANNEL REGIONS                                               ***
C     ******************************************************************
      DO 15 J=1,W
      KR(J)=(AR(J)*A/(2.0*NC(J)*AL(J)))**(1.0/3.0)
      KC(J+W)=AL(J)**(1.0/3.0)
   15 CONTINUE
      DO 20 I=1,WW
      IF(I.GT.W) GO TO 25
      KK(I)=KR(I)
      GO TO 20
   25 KK(I)=KC(I)
   20 CONTINUE
      SSUM=0.0
      DO 5 I=1,MS
      SUM=0.0
      DO 10 J=1,WW
      PK=PATH(I,J)*KK(J)
      SUM=SUM+PK
   10 CONTINUE
      PT=SUM*PS(I)
      SSUM=SSUM+PT
    5 CONTINUE
C     ******************************************************************
C     ***     DETERMINE THE COEFFICIENT AG APPEARING IN THE HOLDING TIME    ***
C     ***     RELATIONSHIP                                                  ***
C     ******************************************************************
      AG=KB/SSUM
C     ******************************************************************
C     ***     DETERMINE THE HOLDING TIMES OF OVERLAND AND CHANNEL REGIONS    ***
C     ******************************************************************
      DO 30 I=1,WW
      TEMP=1.0/(KK(I)*AG)
      KK(I)=TEMP
   30 CONTINUE
      IF(KOPT.NE.0)GO TO 50
      WRITE(6,35)(I,KK(I),I=1,W)
   35 FORMAT(5X,'OVERLAND REGION',1X,I5,5X,'HOLDING TIME(HOURS) IS=',F10
     1.2/)
      DO 60 I=1,W
      WRITE(6,40) I,KK(I+W)
   60 CONTINUE
   40 FORMAT(5X,'CHANNEL ORDER IS=',2X,I5,2X,'HOLDING TIME HOURS IS =',
     1F10.2/)
   50 CONTINUE
      RETURN
```

END

```
      SUBROUTINE IUH(MS,WW,DT,KOPT)
C     ****************************************************************
C     ***   THIS SUBROUTINE COMPUTES THE INSTANTANEOUS UNIT HYDROGRAPH   ***
C     ***   USING GEOMORPHIC FORMULATION                                 ***
C     ****************************************************************
      DIMENSION PATH(20,20),KK(20),NK(20),C(20,20),PS(20),H(2000)
     1,PK(20,20),TT(1000)
      REAL KK
      COMMON/TWO/PATH,PS,KK
      COMMON/THREE/H,NH
      INTEGER WW
C     ******************************************************************
C     ***   DETERMINE THE COEFFICIENTS C(I,J) FOR EACH PATH. THIS REQUIRES ***
C     ***   ANOTHER DETERMINATION OF MATRIX OF COEFFICIENTS ASSOCIATED WITH ***
C     ***   EACH PATH.IN THIS MATRIX ONLY NONZERO VALUES WILL BE RETAINED   ***
C     ******************************************************************
      KNUMB=1000
      DO 5 I=1,MS
      IJ=0
      DO 10 J=1,WW
      IF(PATH(I,J).LE.0.0) GO TO 10
      IJ=IJ+1
      PK(I,IJ)= KK(J)
      NK(I)=IJ
   10 CONTINUE
    5 CONTINUE
      DO 15 I=1,MS
      NKK=NK(I)
      TEMP=1.0
      DO 85 J=1,NKK
      PROD=TEMP*PK(I,J)
      TEMP=PROD
   85 CONTINUE
      DO 20 IK=1,NKK
      STOR=1.0
      DO 25 J=1,NKK
      IF(J.EQ.IK) GO TO 25
      DEN=STOR*(PK(I,J)-PK(I,IK))
      STOR=DEN
   25 CONTINUE
      C(I,IK)=PROD/STOR
   20 CONTINUE
   15 CONTINUE
C     ***************************
C     ***   COMPUTE THE IUH   ***
C     ***************************
      IJ=1
      HMX=0.0
      T=0.1
      H(IJ)=0.0
      TT(1)=0.0
   45 CONTINUE
      SSUM=0.0
      DO 30 I=1,MS
      NKK=NK(I)
      SUM=0.0
      DO 35 J=1,NKK
      PROD=C(I,J)*   EXP(-PK(I,J)*T)*PS(I)
```

```
      SUM=SUM+PP(J)
   35 CONTINUE
      SSUM=SSUM+SUM
   30 CONTINUE
      IJ=IJ+1
      H(IJ)=SSUM
      TT(IJ)=T
      IF(HMX.LT.H(IJ))HMX=H(IJ)
      HMN=0.01*HMX
      IF(H(IJ).GE.KNUMB) GO TO 40
      IF(H(IJ).LT.HMN)GOTO 40
      T=T+DT
      GO TO 45
   40 CONTINUE
      IF(IJ.LT.10) GO TO 30
      NH=IJ
      IF(KOPT.NE.0)GO TO 90
      DO 150 I=1,MS
      NKK=NK(I)
      WRITE(6,60) I
   60 FORMAT(5X,'THIS PATH IS ',I5/)
      WRITE(6,80) (PK(I,J),J=1,NKK)
   80 FORMAT(5X,' PATH HOLDING TIMES ARE '/5X,10F10.4/)
  150 CONTINUE
      DO 155 I=1,MS
      NKK=NK(I)
      WRITE(6,65) I
   65 FORMAT(5X,'THIS PATH IS ',I5/)
      WRITE(6,70) (C(I,J),J=1,NKK)
   70 FORMAT(5X,'PATH COEFFICIENTS C(I,J) ARE '/5X,5E20.7/)
  155 CONTINUE
      WRITE(6,120)
  120 FORMAT(5X,'THE INSTANTANEOUS UNIT HYDROGRAPH IS AS FOLLOWS'//)
C     *************************************
C     ***    CONVERT TIME TO MINUTES    ***
C     *************************************
      DO 125 I=1,NH
  125 TT(I)=TT(I)*60.0
      WRITE(6,130)
  130 FORMAT(7X,'TIME',7X,'IUH',8X,'TIME',7X,'IUH',8X,'TIME',7X,'IUH',7
     1X,'TIME',8X,'IUH',7X,'TIME',9X,'IUH'/)
      WRITE(6,135)
  135 FORMAT(8X,'MN',7X,'1/HR',8X,'MN',8X,'1/HR',8X,'MN',9X,'1/HR',7X,'
     1MN',8X,'1/HR',7X,'MN',9X,'1/HR'/)
      WRITE(6,140)(TT(I),H(I),I=1,NH)
  140 FORMAT(5(F10.1,2X,F10.2))
   90 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PRECIP(NNQ,DT,AA,OBQ,OBQT,A)
C     ******************************************************************
C     ***    THIS SUBROUTINE COMPUTES RAINFALL-EXCESS AND ARRANGES THE  ***
C     ***    INPUT IN A PROPER FASHION                                  ***
C     ******************************************************************
      DIMENSION IT1(100),IT2(100),QI(100),TI(100),X(2000)
     1,INF(20),         JTQ1(200),JTQ2(200),TQ(200),OCB(200),INFO(20)
     2,PHI(100)
      COMMON/VS/TI,QI
      COMMON/VSX/X
      COMMON/VPS/PHI
C     ******************************************************************
C     ***   FAC=2.54, CONVERSION FACTOR FROM INCH TO CENTIMETERS       ***
C     ******************************************************************
      FAC=2.54
C     ****************************************************************
C     ***    READ RAINFALL INPUT. TIME IS IN HOUR-MINUTE SYSTEM , AND ***
C     ***     INTENSITY IN INCHES PER HOUR                            ***
C     ***   NNQ= NUMBER OF RAINFALL READINGS                          ***
C     ***    S= SORPTIVITY, PARAMETERS IN PHILIP INFILTRATION MODEL   ***
C     ****************************************************************
      READ(5,1) NNQ
    1 FORMAT(I5,10X,F10.4)
      WRITE(6,11) NNQ
   11 FORMAT(5X,' NO OF  RAINFALL READINGS',I5/)
C     ************************************************************
C     ***   INF= DATE OF THE EVENT AND THE WATERSHED IT OCCURED ON  ***
C     ************************************************************
      READ(5,3) (INF(I),I=1,20)
    3 FORMAT(20A4)
      WRITE(6,3) (INF(I),I=1,20)
C     ******************************************************************
C     ***  RVOL= VOLUME OF RAINFALL AND QVOL= VOLUME OF SURFACE RUNOFF  ***
C     ******************************************************************
      READ(5,518) RVOL,QVOL
  518 FORMAT(2F10.4)
      RVOL=RVOL*FAC
      QVOL=QVOL*FAC
      WRITE(6,618) RVOL,QVOL
  618 FORMAT(5X,'RAINFALL VOLUME IS ',F10.4,5X,'RUNOFF VOLUME IS ',F10.4
     1)
C     ****************************************************************
C     ***   IT1= CLOCK-HOUR  , IT2= MINUTE AND QI= RAINFALL INTENSITY   ***
C     ****************************************************************
      READ(5,2)(IT1(I),IT2(I),QI(I),I=1,NNQ)
    2 FORMAT((4(2I5,F10.4)))
      DO 700 I=1,NNQ
  700 QI(I)=QI(I)*FAC
      WRITE(6,7)
    7 FORMAT(5X,'TIME',3X,'INTENSITY',4X,'TIME',3X,'INTENSITY',4X,'TIME'
     1,3X,'INTENSITY',4X,'TIME',3X,'INTENSITY'/)
      WRITE (6,8)
    8 FORMAT(2X,'HOUR',1X,'MIN',4X,'CM/HR',3X,'HOUR',1X,'MIN',4X,'CM/HR'
     1,3X,'HOUR',1X,'MIN',4X,'CM/HR',3X,'HOUR',1X,'MIN',4X,'CM/HR'/)
      WRITE(6,2) (IT1(I),IT2(I),QI(I),I=1,NNQ)
C     *************************************************************
C     ***   REDUCE CLOCK-HOUR TIMES TO ABSOLUTE TIMES IN SECONDS    ***
C     ***    BEGINNING WITH ZERO                                    ***
```

```
C       ***    CHANGE TIME TO SECONDS                                      ***
C       ******************************************************************
        TI(1)=0.0
        DO 12 I=2,NNQ
        IF(IT1(I)  - IT1(I-1)) 14,13,14
     13 TI(I)=(IT2(I)-IT2(I-1))*60.00+TI(I-1)
        GO TO 15
     14 IF(IT1(I)  - IT1(I-1)) 17,17,16
     16 TI(I)=TI(I-1)+60.00*IT2(I)+(60-IT2(I-1))*60.00+3600.00*(IT1(I)-
       1IT1(I-1)-1)
        GO TO 15
     17 TI(I)=TI(I-1)+60.00*IT2(I)+3600.00*IT1(I)+60.00*(60-IT2(I-1))+
       1(24-IT1(I-1)-1)*3600.00
     15 CONTINUE
     12 CONTINUE
        DO 21 I=1,NNQ
     21 TI(I)=TI(I)/60.0
        TTFIN=TI(NNQ)
        WRITE(6,19)
     19 FORMAT(7X,'TIME',3X,'INTENSITY',4X,'TIME',3X,'INTENSITY',4X,'TIME'
       1,3X,'INTENSITY',4X,'TIME',3X,'INTENSITY'/)
        WRITE(6,20)
     20 FORMAT(9X,'MN',6X,'CM/HR',6X,'MN',6X,'CM/HR',6X,'MN',6X,'CM/HR'
       1,6X,'MN',6X,'CM/HR'/)
        WRITE(6,18) (TI(I),QI(I),I=1,NNQ)
     18 FORMAT(4(F10.1,F10.4))
C       ****************************************
C       ***    COMPUTE VOLUME OF RAINFALL (CM)  ***
C       ****************************************
        MNQ=NNQ-1
        VRAIN=0.0
        DO 135 I=1,MNQ
        VRAIN=VRAIN+(QI(I)*(TI(I+1)-TI(I))/60.0)
    135 CONTINUE
        WRITE(6,140)VRAIN
    140 FORMAT(5X,'COMPUTED VOLUME OF RAINFALL (CM)=',F10.3//)
C       **********************************************************************
C       ***    READ OBSERVED RUNOFF INPUT . TIME IS IN HOUR-MINUTE SYSTEM   ***
C       ***    ,AND RUNOFF IN INCHES PER HOUR                                ***
C       ***   NQQ= NUMBER OF RUNOFF READINGS                                 ***
C       **********************************************************************
        READ(5,4) NQQ
      4 FORMAT(I5)
        WRITE(6,41) NQQ
     41 FORMAT(5X,' NO OF RUNOFF READINGS ',I5/)
C       *****************************************************************
C       ***   INFQ= DATE OF RUNOFF EVENT AND THE WATERSHED IT OCCURED ON  ***
C       *****************************************************************
        READ(5,5) (INFQ(I),I=1,20)
        WRITE(6,5)(INFQ(I),I=1,20)
      5 FORMAT(20A4)
C       ******************************************************
C       ***   JTQ1= CLOCK-HOUR, JTQ2=MINUTE AND QOB= DISCHARGE  ***
C       ******************************************************
        READ(5,6) (JTQ1(I),JTQ2(I),QOB(I),I=1,NQQ)
      6 FORMAT((4(2I5,F10.4)))
        DO 705 I=1,NQQ
    705 QOB(I)=QOB(I)*FAC
```

```
      WRITE(6,9)
    9 FORMAT(5X,'TIME',6X,'RUNOFF',4X,'TIME',6X,'RUNOFF',4X,'TIME',6X,
     1'RUNOFF',4X,'TIME',6X,'RUNOFF'/)
      WRITE(6,8)
      WRITE(6,6) (JTQ1(I),JTQ2(I),QOB(I),I=1,NQQ)
C     ***********************************
C     ***    CHANGE TIME TO SECONDS    ***
C     ***********************************
      TQ(1)=0.00
      DO 55 I=2,NQQ
      IF(JTQ1(I)  - JTQ1(I-1)) 52,51,52
   51 TQ(I)=(JTQ2(I)-JTQ2(I-1))*60+TQ(I-1)
      GO TO 53
   52 IF(JTQ1(I)  - JTQ1(I-1)) 56,56,54
   54 TQ(I)=TQ(I-1)+60*JTQ2(I)+(60-JTQ2(I-1))*60+3600*(JTQ1(I)-JTQ1(I-
     11)-1)
      GO TO 53
   56 TQ(I)=TQ(I-1)+60*JTQ2(I)+3600*JTQ1(I)+60*(60-JTQ2(I-1))+(24-JTQ1
     1(I-1)-1)*3600
   53 CONTINUE
   55 CONTINUE
C     *********************************************************
C     ***    SORT OUT THE PEAK RATE OF RUNOFF OBSERVED     ***
C     ***    OBQ=PEAK RUNOFF                                ***
C     *********************************************************
      JP=1
      OBQ=QOB(1)
      DO 25 I=2,NQQ
      TQ(I)=TQ(I)/60.0
      IF(OBQ.GT.QOB(I)) GO TO 25
      OBQ=QOB(I)
      JP=I
   25 CONTINUE
      OBQT=TQ(JP)
      WRITE(6,27)
   27 FORMAT(7X,'TIME',5X,'RUNOFF',3X,'TIME',5X,'RUNOFF',6X,'TIME',6X,'
     1RUNOFF',6X,'TIME',3X,'RUNOFF'/)
      WRITE(6,26)
   26 FORMAT(8X,'MN',6X,'CM/HR',7X,'MN',6X,'CM/HR',7X,'MN',6X,'CM/HR',7
     1X,'MN',6X,'CM/HR'/)
      WRITE(6,18)(TQ(I),QOB(I),I=1,NQQ)
C     ***********************************************
C     ***    COMPUTE VOLUME OF SURFACE RUNOFF(CM)   ***
C     ***********************************************
      VRUNOF=0.0
      DO 145 I=2,NQQ
      VRUNOF=VRUNOF+(QOB(I)+QOB(I-1))*0.5*(TQ(I)-TQ(I-1))/60.0
  145 CONTINUE
      QVOL=VRUNOF
      WRITE(6,150) VRUNOF
  150 FORMAT(5X,'COMPUTED VOLUME OF SURFACE RUNOFF(CM)=',F10.4/)
C     ***************************************************
C     ***   CHANGE RUNOFF TO CUBIC METERS PER SECOND  ***
C     ***************************************************
      DO 715 I=1,NQQ
  715 QOB(I)=QOB(I)*A*100.0/36.0
      WRITE(6,27)
      WRITE(6,720)
```

```
  720 FORMAT(8X,'MN',6X,'CUM/S',7X,'MN',6X,'CUM/S',7X,'MN',6X,'CUM/S',
     17X,'MN',6X,'CUM/S'/)
      WRITE(6,18) (TQ(I),QOB(I),I=1,NQQ)
C     ******************************************************************
C     ***   COMPUTE INFILTRATION LOSS ,AND SUBTRACT IT FROM RAINFALL   ***
C     ******************************************************************
      DO 115 I=1,NNQ
  115 TI(I)=TI(I)/60.0
      CALL NEWTON(NNQ,QVOL,S,AA)
      WRITE(6,125)S,AA
  125 FORMAT(5X,'PHILIP PARAMETER S(CM/SQRT(HR))=',F10.4//5X,'PHILIP
     1PARAMETER A(CM/HR)=',F10.4/)
      CALL INFIL(NNQ,S,AA)
C     ************************************************
C     ***  DETERMINE THE RAINFALL-EXCESS VOLUME(CM)   ***
C     ************************************************
      VEXCES=0
      DO 69 I=1,NNQ
      RLOSS=(PHI(I)+PHI(I+1))*0.5
      QI(I)=QI(I)-RLOSS
      IF(QI(I).LT.0.00) QI(I)=0.00
      TEMP=TI(I+1)-TI(I)
      VEXCES=VEXCES+QI(I)*TEMP
   69 CONTINUE
      QI(NNQ)=0.00
      NNQ=NNQ+1
      TI(NNQ)=TI(NNQ-1)+0.5
      QI(NNQ)=0.0
      WRITE(6,130)VEXCES
  130 FORMAT(5X,'COMPUTED VOLUME OF RAINFALL EXCESS(CM)=',F10.4/)
      DO 120 I=1,NNQ
  120 TI(I)=TI(I)*60.0
      WRITE(6,627)
  627 FORMAT(5X,'RAIN INFILTRATION IS AS FOLLOWS '//)
      WRITE(6,110)
  110 FORMAT(7X,'TIME',4X,'INFIL',7X,'TIME',4X,'INFIL',6X,'TIME',5X,
     1'INFIL',5X,'TIME',5X,'INFIL'/)
      WRITE(6,26)
      WRITE(6,18) (TI(I),PHI(I),I=1,NNQ)
C     ********************************
C     ***   ADJUST THE TIME SCALE   ***
C     ********************************
      IF(QI(1)  - 0.00) 92,92,91
   91 IF(TI(NNQ)  - TTFIN) 93,93,90
   93 NNQ=NNQ+1
      TI(NNQ)=TTFIN+10.00
      QI(NNQ)=0.00
      GO TO 90
   92 CONTINUE
      IK=0
      IFRP=0
      DO 76 I=1,NNQ
      IN=I
      PTMP=QI(I)
      IF(PTMP-0.00) 76,76,77
   77 IK=IK+1
      TMP=TI(I)
      GO TO 78
```

```
   76 CONTINUE
   78 CONTINUE
      IF(IK.EQ.0) IERR=-1
      IF(IERR.EQ.-1) GO TO 23
      DO 79 I=IN,NNQ
      PTMP=QI(I)
      QI(IK)=PTMP
      TI(IK)=TI(I)-TMP
      IK=IK+1
   79 CONTINUE
      QI(IK)=0.00
      TI(IK)=TI(IK-1)+10.00
      IK=IK+1
      QI(IK)=0.00
      TI(IK)=TI(IK-1)+10.00
      NNQ=IK
   90 CONTINUE
C     ******************************************
C     ***   SORTOUT THE PEAK RATE OF RAINFALL   ***
C     ***  QIMAX= PEAK RAINFALL INTENSITY       ***
C     ******************************************
      QIMAX=QI(1)
      DO 22 I=2,NNQ
      IF(QIMAX.GT.QI(I)) GO TO 22
      QIMAX=QI(I)
   22 CONTINUE
C     WRITE(6,24) QIMAX,QBQ
C  24 FORMAT(5X,*PEAK RAINFALL INTENSITY (CM/HR)*,F10.4,2X,*PEAK RUNOFF
C    1(CM/HR)*,F10.4)
   23 CONTINUE
      WRITE(6,628)
  628 FORMAT(5X,'RAINFALL-EXCESS IS AS FOLLOWS '//)
      WRITE(6,19)
      WRITE(6,20)
      WRITE(6,18)(TI(I),QI(I),I=1,NNQ)
      WRITE(6,160) TMP
  160 FORMAT(5X,'LAG TIME BETWEEN THE START OF RAINFALL AND THE
     1EFFECTIVE RAINFALL (MIN)=',F10.2/)
      RETURN
      END
```

```
      SUBROUTINE XDATA(NNQ,NXM,DT)
C     ****************************************************************
C     ***    THIS SUBROUTINE COMPUTES THE RAINFALL EXCESS AT EQUAL   ***
C     ***    TIME INTEPVAL                                            ***
C     ****************************************************************
      DIMENSION QI(100),TI(100),X(2000)
      COMMON/VS/TI,QI
      COMMON/VSX/X
C     *************************************
C     ***    DEFINE LIMIT OF COMPUTATION    ***
C     *************************************
      DO 40 I=1,NNQ
      TI(I)= TI(I)/60.0
   40 CONTINUE
      NMAX=NXM
      QI(NNQ+1)=0.0
      TI(NNQ+1)=TI(NNQ)+500.0*DT
      NXM=TI(NNQ)/DT+1.0
      IF(NXM.LT.NMAX) NXM=NMAX+5
      TC=0.0
      KK=1
      DO 60 I=1,NXM
      IF(TC.GT.TI(KK)) GO TO 65
      GO TO 70
   65 X(I)=((TI(KK)-(TC-DT))*QI(KK)+(TC-TI(KK))*QI(KK+1))/DT
      KK=KK+1
      GO TO 75
   70 X(I)=QI(KK)
   75 CONTINUE
      TC=TC+DT
   60 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE NEWTON(NNQ,YEXCES,X3,B)
C     ******************************************************************
C     ***   THIS SUBROUTINE COMPUTES THE SORPTIVITY PARAMETERS IN THE  ***
C     ***   PHILIP TWO-TERM INFILTRATION MODEL.                        ***
C     ******************************************************************
      DIMENSION TI(100),QI(100),PHI(100)
      COMMON/VPS/PHI
      COMMON/VS/TI,QI
      X1=0.10
      X2=2.5
      KOUNT=0
   10 CONTINUE
      CALL INFIL(NNQ,X1,B)
      MNQ=NNQ-1
      VEXCES=0.00
      DO 60 I=1,MNQ
      AVG=(PHI(I)+PHI(I+1))*0.5
      DIFQ=QI(I)-AVG
      IF(DIFQ.LT.0.00) DIFQ=0.00
      VEXCES=VEXCES+DIFQ*(TI(I+1)-TI(I))
   60 CONTINUE
      FX1=VEXCES-YEXCES
      CALL INFIL(NNQ,X2,B)
      MNQ=NNQ-1
      VEXCES=0.00
      DO 55 I=1,MNQ
      AVG=(PHI(I)+PHI(I+1))*0.5
      DIFQ=QI(I)-AVG
      IF(DIFQ.LT.0.00) DIFQ=0.00
      VEXCES=VEXCES+DIFQ*(TI(I+1)-TI(I))
   55 CONTINUE
      FX2=VEXCES-YEXCES
      DFX=FX2-FX1
      IF(DFX.NE.0.00) GO TO 6
      X3=2.0*X2
      GO TO 7
    6 CONTINUE
      X3=(X1*FX2-X2*FX1)/DFX
    7 CONTINUE
      ERR=ABS((YEXCES-VEXCES)/YEXCES)
      KOUNT=KOUNT+1
      IF(ERR.LT.0.01) GO TO 25
      IF (KOUNT.GT.20) GO TO 30
      X1=X2
      X2=X3
      GO TO 10
   30 CONTINUE
      WRITE(6,36)
   36 FORMAT(5X,'ERROR IN THE LOOP AND NO CONVERGENCE'/)
   25 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE INFIL(NNQ,S,A)
C     ******************************************************************
C     ***    THIS SUBROUTINE COMPUTES INFILTRATION USING THE TWO- TERM   ***
C     ***    INFILTRATION MODEL                                          ***
C     ******************************************************************
      DIMENSION TI(100),PHI(100)
      COMMON/VS/TI
      COMMON/VPS/PHI
C     ***************************************
C     ***    TWO PARAMETERS ARE S AND A    ***
C     ***************************************
      DO 5 I=2,NNQ
      TEMP=TI(I)
      PHI(I)=0.5*S*TEMP**(-0.5)+A
    5 CONTINUE
      PHI(1)=PHI(2)
      RETURN
      END
```

```
      SUBROUTINE BROSEN(N,MST,IPT,EPS,NOBS)
      DIMENSION E(10),B(10),C(10),D(10),IS(10),X(10),Y(10),Z(10),
     1XM(10),XL(10),S(10,10),NR(10)
      COMMON/PARA/X,XL,XM
      COMMON/ROSE/Y
C     ***************************************************************
C     THIS PROGRAM SOLVES CONSTRAINED MINIMIZATION PROBLEM, WHICH     ***
C     REQUIRES THAT THE VECTOR ALWAYS BE AN INTERIOR POINT OF THE     ***
C     FEASIBLE SET                                                     ***
C     THE SOLUTION TECHNIQUE IS A MIXED APPLICATION OF ORIGINAL        ***
C     ROSENBROCK METHOD, PALMER VERSION AND PENALTY FUNCTION METHOD    ***
C     THE USER MUST SUPPLY A SUBROUTINE OBJECT(VALUE,NOBS,N) FOR       ***
C     EVALUATION OF THE OBJECTIVE FUNCTION                             ***
C     THE USER MUST ALSO PROVIDE THE FOLLOWING INFORMATION              ***
C     N= NUMBER OF VARIABLES                                           ***
C     X(I)= INITIAL GUESS OF THE VECTOR                                ***
C     XM(I)= UPPER LIMIT OF THE PARAMETER X(I)                         ***
C     XL(I)= LOWER LIMIT OF THE PARAMETER X(I)                         ***
C     EPS= CONVERGENCE TOLERANCE BASED ON THE CHANGE OF OBJECTIVE      ***
C          FUNCTION                                                    ***
C     MST= MAXIMUM LIMIT OF NUMBER OF STAGE SEARCH                     ***
C     IPT= 0 --- ONLY THE FINAL ANSWER IS DESIRED TO BE PRINTED        ***
C     IPT= 1 --- INTERMEDIATE VALUES OF EACH STAGE SEARCH IS DESIRED   ***
C     TO BE PRINTED                                                    ***
C     IPT= 2 --- INTERMEDIATE VALUES OF EACH CYCLE SEARCH IS DESIRED   ***
C     TO BE PRINTED                                                    ***
C     SET INITIAL STEP LENGTH AND DIRECTION                            ***
C     ***************************************************************
      DO 1 I=1,N
      D(I)=0.1*X(I)
      Y(I)=X(I)
      DO 2 J=1,N
      S(I,J)=0.
      IF(J.EQ.I) S(I,J)=1.
    2 CONTINUE
    1 CONTINUE
C     ******************************
C     STARTING OF STAGE SEARCH    ***
C     ******************************
      NS=-1
      NEF=1
      CALL OBJECT(VALUE,NOBS,N)
      PO=VALUE
    3 NS=NS+1
      OBJ=PO
      DO 4 I=1,N
      NR(I)=0
      IS(I)=0
      Z(I)=0.
    4 CONTINUE
      IF(IPT.EQ.0) GO TO 5
      WRITE(6,650)
  650 FORMAT(/40X,40H****************************************)
      WRITE(6,604) NS
  604 FORMAT(//48X,18HSTAGE SEARCH -----,I5)
C     ***********************************************************
C     STARTING OF CYCLE SEARCH (WITHOUT CHANGING SEARCH DIRECTION)   ***
C     ***********************************************************
```

```
    5 NC=-1
    6 NC=NC+1
      DO 7 I=1,N
      ICON=0
      DX=D(I)
   32 DO 8 J=1,N
      Y(J)=X(J)+DX*S(I,J)
C     ***********************************************************
C     CHECK IF IT IS AN INTERIOR POINT OF THE FEASIBLE SET     ***
C     ***********************************************************
      IF(Y(J).LT.XL(J) .OR. Y(J).GT.XM(J)) ICON=1
    8 CONTINUE
      IF(ICON.NE.1) GO TO 25
      DMIN=1.0E10
      DO 26 J=1,N
      IF(S(I,J).EQ.0.) GO TO 26
      IF(Y(J).GT.XL(J)) GO TO 30
      DD=ABS((X(J)-XL(J))/S(I,J))
      IF(DD.LT.DMIN) DMIN=DD
   30 IF(Y(J).LT.XM(J)) GO TO 26
      DD=ABS((X(J)-XM(J))/S(I,J))
      IF(DD.LT.DMIN) DMIN=DD
   26 CONTINUE
      IF(DX.LT.0.) DMIN=-DMIN
      DX=DMIN
      ICON=2
      GO TO 32
   25 NEF=NEF+1
      CALL OBJECT(VALUE,NOBS,N)
C     ***********************************************************
C     CHECK IF THE VALUE OF OBJECTIVE FUNCTION IS IMPROVED     ***
C     ***********************************************************
      IF(VALUE.GT.PO) GO TO 9
C     ************************************************************
C     THE VALUE OF OBJECTIVE FUNCTION IS IMPROVED (SUCCESS)     ***
C     ************************************************************
      PO=VALUE
      IF(ICON.EQ.2) GO TO 33
      IF(IS(I).NE.2) IS(I)=1
      Z(I)=Z(I)+D(I)
      D(I)=3.*D(I)
      GO TO 31
   33 Z(I)=Z(I)+DMIN
      D(I)=-DMIN-0.5*D(I)
      IS(I)=2
   31 DO 10 J=1,N
      X(J)=Y(J)
   10 CONTINUE
      GO TO 7
C     ***************************************************************
C     THE VALUE OF OBJECTIVE FUNCTION IS NOT IMPROVED (FAILURE)   ***
C     ***************************************************************
    9 IF(IS(I).EQ.1) IS(I)=2
      D(I)=-0.5*D(I)
    7 CONTINUE
C     *************************
C     END OF CYCLE SEARCH   ***
C     *************************
```

```
      IF(IPT.NE.2) GO TO 11
      WRITE(6,605) NC
  605 FORMAT(//48X,18HCYCLE SEARCH -----,I5)
      WRITE(6,606) PO
  606 FORMAT(//34X,32HTHE CURRENT OBJECTIVE FUNCTION =,E20.8//50X,21HTHE
     1 CURRENT VECTOR IS)
      WRITE(6,603) (X(I),I=1,N)
C     ***************************************************************
C     CHECK IF ALL THE SEARCH DIRECTION HAVE FAILED AT LEAST ONCE    ***
C     FOLLOWED BY A SUCCESS                                          ***
C     ***************************************************************
   11 IPT=0
      DO 12 I=1,N
      IF(IS(I).NE.2) IPT=1
      IF(IS(I).EQ.0) NR(I)=NR(I)+1
   12 CONTINUE
      DO 34 I=1,N
      IF(NR(I).LT.4) GO TO 35
   34 CONTINUE
      GO TO 14
   35 IF(IPT.EQ.1) GO TO 6
C     *************************
C     END OF STAGE SEARCH    ***
C     *************************
      IF(IPT.EQ.0) GO TO 13
      WRITE(6,650)
      NC=NC+1
      WRITE(6,607) NC
  607 FORMAT(//41X,30HTOTAL NUMBER OF CYCLE SEARCH =,I5)
      WRITE(6,606) PO
      WRITE(6,603) (X(I),I=1,N)
C     *********************************************************************
C     CHECK IF THE RESULT IS SATISFIED WITH THE PREASSIGNED CONVERGENCE   ***
C     TOLERANCE                                                           ***
C     *********************************************************************
   13 IF((OBJ-PO).LE.EPS) GO TO 14
C     ******************************************************************
C     CHECK IF THE NUMBER OF STAGE SEARCH GREATER THAN ASSIGNED LIMIT   ***
C     ******************************************************************
      IF(NS.LT.MST) GO TO 15
      WRITE(6,650)
      WRITE(6,608) MST
  608 FORMAT(//40X,18HDO NOT CONVERGE IN,I5,5X,14HSTAGE SEARCHES)
      WRITE(6,606) PO
      WRITE(6,603) (X(I),I=1,N)
  603 FORMAT(2F10.4,F10.1)
      GO TO 700
C     ********************************************************
C     CALCULATE NEW SEARCH DIRECTION FOR NEXT STAGE SEARCH   ***
C     PALMERS VERSION IS USED TO COMPUTE THE NEW DIRECTION   ***
C     ********************************************************
   15 DO 17 I=1,N
      SUMA=0.
      DO 18 J=1,N
      E(J)=0.
      DO 19 K=1,N
      E(J)=E(J)+Z(K)*S(K,J)
   19 CONTINUE
```

```
      SUMA=SUMA+E(J)**2
   18 CONTINUE
      AA=SQRT(SUMA)
      IF(AA.EQ.0.) GO TO 3
      IF(I.EQ.1) GO TO 20
      IF(ABS(Z(I-1)).LE.EPS) GO TO 27
      DA=1./SQRT(AB**2-AA**2)
      RA=AB/AA
      CA=DA*RA
      CB=DA/RA
      DO 21 J=1,N
      C(J)=S(I,J)
      S(I,J)=E(J)*CA-B(J)*CB
      B(J)=E(J)
   21 CONTINUE
      GO TO 23
   20 DO 22 J=1,N
      C(J)=S(I,J)
      S(I,J)=E(J)/AA
      B(J)=E(J)
   22 CONTINUE
      GO TO 23
   27 DO 28 J=1,N
      CTEM=S(I,J)
      S(I,J)=C(J)
      C(J)=CTEM
      B(J)=E(J)
   28 CONTINUE
   23 AB=AA
   17 CONTINUE
      GO TO 3
C     ******************************
C     A MINIMUM HAS BEEN FOUND    ***
C     ******************************
   14 NS=NS+1
      WRITE(6,650)
      WRITE(6,609) NS,NEF
  609 FORMAT(//48X,24HA MINIMUM HAS BEEN FOUND//41X,30HTOTAL NUMBER OF S
     1TAGE SEARCH =,I5//39X,37HTOTAL NUMBER OF FUNCTION EVALUATION =,I5)
      WRITE(6,610) PO
  610 FORMAT(//38X,23HOPTIMIZATION FUNCTION =,E20.8//50X,15HFINAL VECTOR
     1 IS)
      WRITE(6,633) (X(I),I=1,N)
  700 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CONVOL(DT,NXM,QP,QPT,KOPT,A)
C     ******************************************************************
C     ***    THIS SUBROUTINE CONVOLUTES THE RAINFALL EXCESS WITH     ***
C     ***    THE INSTANTANEOUS UNIT HYDROGRAPH TO DETERMINE THE      ***
C     ***    DIRECT RUNOFF HYDROGRAPH                                ***
C     ******************************************************************
      DIMENSION H(2000),X(2000),Y(2000),TY(2000)
      COMMON/THREE/H,NH
      COMMON/VSX/X
      KNUMB=2000
      NHA=NH+1
      NHB=NH+NXM
      IF(NHB.GT.KNUMB) NHB=KNUMB
      NYM=NHB-1
      DO 30 I=NHA,NHB
      H(I)=0.0
   30 CONTINUE
      MXM=NXM+1
      DO 10 I=MXM,NHB
      X(I)=0.0
   10 CONTINUE
      TC=0.0
      YMX=0.0
      YB=0.0
      DO 35 N=1,NYM
      TC=TC+DT
      Y(N)=0.0
      TY(N)=TC
      J=N
      IF(N.GT.NXM) J=NXM
      DO 40 I=1,J
      IA=N+1-I
      Y(N)=Y(N)+X(I)*H(IA)
   40 CONTINUE
      Y(N)=Y(N)*DT
      IF(YMX.LT.Y(N)) YMX=Y(N)
      YMN=0.01*YMX
      NOY=N
      IF(N.GE.KNUMB) GO TO 45
      IF(Y(N).LT.YMN.AND.N.GT.20) GO TO 45
   35 CONTINUE
   45 CONTINUE
      DO 5 I=1,NOY
      TEMP=TY(NOY+1-I)
      TY(NOY-I+2)=TEMP
    5 CONTINUE
      TY(1)=0.0
      NOY=NOY+1
      DO 15 I=1,NOY
   15 TY(I)=TY(I)*60.0
C     **********************************************************************
C     ***    SORT OUT THE PEAK RATE OF SURFACE RUNOFF AND ITS TIME OF    ***
C     ***    OCCURRENCE                                                  ***
C     **********************************************************************
      QP=Y(1)
      DO 50 I=2,NOY
      IF(QP.GT.Y(I)) GO TO 50
      QP=Y(I)
```

```
      IP=1
   50 CONTINUE
      QPT=TY(IP)
      IF(KOPT.NE.0)GO TO 60
      WRITE(6,145)
  145 FORMAT(5X,'THE SURFACE RUNOFF HYDROGRAPH IS AS FOLLOWS'//)
      WRITE(6,150)
  150 FORMAT(7X,'TIME',6X,'RUNOFF',5X,'TIME',5X,'RUNOFF',7X,'TIME',5X,'
     1RUNOFF',5X,'TIME',5X,'RUNOFF'/)
      WRITE(6,155)
  155 FORMAT(8X,'MN',7X,'CM/HR',7X,'MN',8X,'CM/HR',7X,'MN',8X,'CM/HR',7
     1X,'MN',8X,'CM/HR'/)
      WRITE(6,160) (TY(J),Y(J),J=1,NOY)
  160 FORMAT(4(F10.1,2X,F10.3))
C     *************************************************
C     ***  CHANGE RUNOFF TO CUBIC METERS PER SECOND  ***
C     *************************************************
      FAC=A*100.0/36.0
      DO 170 I=1,NOY
  170 Y(I)=Y(I)*FAC
      WRITE(6,150)
      WRITE(6,175)
  175 FORMAT(8X,'MN',7X,'CUM/S',7X,'MN',8X,'CUM/S',7X,'MN',8X,'CUM/S'
     1,7X,'MN',7X,'CUM/S'/)
      WRITE(6,160) (TY(J),Y(J),J=1,NOY)
   60 CONTINUE
      RETURN
      END
```

MILITARY HYDROLOGY REPORTS

Report No.	No. in Series	Title	Date
TR EL-79-2	-	Proceedings of the Military Hydrology Workshop, 17-19 May 1978, Vicksburg, Mississippi	May 1979
MP EL-79-6 (Military Hydrology Series)	1	Status and Research Requirements	Dec 1979
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	6	Assessment of Two Currently "Fieldable" Geophysical Methods for Military Ground-Water Detection	Oct 1984
	7	A Statistical Summary of Ground-Water Yield, Depth, and Quality Data for Selected Areas in the CENTCOM Theatre of Operations (U)	Oct 1984
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	12	Case Study Evaluation of Alternative Dam-Breach Flood Wave Models	Nov 1986
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	15	The Seismic Refraction Compression-Shear Wave Velocity Ratio as an Indicator of Shallow Water Tables: A Field Test	Nov 1987
	16	Assessment of Shuttle Imaging Radar and Landsat Imagery for Ground-Water Exploration in Arid Environments	Jun 1989
	17	A Quasi-Conceptual Linear Model for Synthesis of Direct Runoff with Potential Application to Ungaged Basins	Jul 1989
Unnumbered		Proceedings of the Ground-Water Detection Workshop, 12-14 January 1982, Vicksburg, Mississippi	Dec 1984